

A Principled Framework for Constructing Natural Language Interfaces to Temporal Databases

Ioannis Androutsopoulos



Ph.D.
University of Edinburgh
1996

Abstract

Most existing natural language interfaces to databases (NLIDBs) were designed to be used with “snapshot” database systems, that provide very limited facilities for manipulating time-dependent data. Consequently, most NLIDBs also provide very limited support for the notion of time. In particular, they were designed to answer questions that refer mainly to the present, and do not support adequately the mechanisms that natural language uses to express time. The database community is becoming increasingly interested in *temporal* database systems. These are intended to store and manipulate in a principled manner information not only about the present, but also about the past and future. When interfacing to temporal databases, it becomes crucial for NLIDBs to interpret correctly temporal linguistic mechanisms (verb tenses, temporal adverbials, temporal subordinate clauses, etc.)

I argue that previous approaches to natural language interfaces for *temporal* databases (NLITDBs) are problematic, mainly because they ignore important time-related linguistic phenomena, and/or they assume idiosyncratic temporal database systems. This thesis develops a principled framework for constructing English NLITDBs, drawing on research in tense and aspect theories, temporal logics, and temporal databases. I first explore temporal linguistic phenomena that are likely to appear in English questions to NLITDBs. Drawing on existing linguistic theories of time, I formulate an account for a large number of these phenomena that is simple enough to be embodied in practical NLITDBs. Exploiting ideas from temporal logics, I then define a temporal meaning representation language, TOP, and I show how the HPSG grammar theory can be modified to incorporate the tense and aspect account of this thesis, and to map a wide range of English questions involving time to appropriate TOP expressions. Finally, I present and prove the correctness of a method to translate from TOP to TSQL2, TSQL2 being a temporal extension of the SQL-92 database language. This way, I establish a sound route from English questions involving time to a general-purpose temporal database language, that can act as a principled framework for building NLITDBs. To demonstrate that this framework is workable, I employ it to develop a prototype NLITDB, implemented using the ALE grammar development system and Prolog. The prototype NLITDB can map temporal questions from a non-trivial fragment of English to appropriate TSQL2 queries.

Acknowledgements

I would like to thank my supervisors, Dr. Graeme Ritchie and Dr. Peter Thanisch, for their guidance throughout my studies in Edinburgh. The work that this thesis reports was supported by a scholarship from the Greek State Scholarships Foundation, to which I am grateful.

The ALE grammar of the prototype NLITDB (chapter 6) is based on previous ALE encodings of HPSG fragments by Gerald Penn, Bob Carpenter, Suresh Manandhar, and Claire Grover. I am indebted to all of them. I am also grateful to Chris Brew, who provided additional ALE code for displaying feature-structures, and to Jo Calder, for his help with ALE, HPSG-PL, and PLEUK.

This thesis is dedicated to my parents, whose continuous support I find invaluable.

Declaration

I hereby declare that I composed this thesis entirely myself and that it describes my own research.

Ioannis Androutsopoulos
Edinburgh
June 1996

Contents

Abstract	ii
Acknowledgements	iii
Declaration	iv
List of Tables	xii
List of Figures	xiii
Index of Symbols	xiv
1 Introduction	1
1.1 Subject of this thesis	1
1.2 Some background	2
1.2.1 Natural language interfaces to databases	2
1.2.2 Tense and aspect theories	3
1.2.3 Temporal logics	6
1.2.4 Temporal databases	7
1.3 Contribution of this thesis	10
1.4 Issues that will not be addressed	12
1.5 Outline of the remainder of this thesis	14
2 The Linguistic Data and an Informal Account	16
2.1 Introduction	16
2.2 Aspectual taxonomies	17

2.3	The aspectual taxonomy of this thesis	18
2.4	Criteria for classifying base verb forms	20
2.4.1	The simple present criterion	20
2.4.2	The point criterion	22
2.4.3	The imperfective paradox criterion	23
2.4.4	Other criteria	24
2.4.5	Classifying base verb forms in the airport domain	24
2.5	Verb tenses	27
2.5.1	Simple present	28
2.5.2	Simple past	29
2.5.3	Present continuous and past continuous	30
2.5.4	Present perfect	33
2.5.5	Past perfect	35
2.6	Special temporal verbs	37
2.7	Temporal nouns	38
2.8	Temporal adjectives	38
2.9	Temporal adverbials	39
2.9.1	Punctual adverbials	39
2.9.2	Period adverbials	44
2.9.3	Duration “for . . . ” adverbials	49
2.9.4	Duration “in . . . ” adverbials	52
2.9.5	Other temporal adverbials	54
2.10	Temporal subordinate clauses	54
2.10.1	“While . . . ” clauses	55
2.10.2	“Before . . . ” and “after . . . ” clauses	58
2.10.3	Tense coordination	63
2.11	Noun phrases and temporal reference	63
2.12	Temporal anaphora	66
2.13	Other phenomena that are not supported	67
2.14	Summary	69

3	The TOP Language	73
3.1	Introduction	73
3.2	Syntax of TOP	74
3.3	The temporal ontology	79
3.4	TOP model	81
3.5	Variable assignment	83
3.6	Denotation of a TOP expression	84
3.7	The Pres operator	88
3.8	The Past operator	91
3.9	Progressives, non-progressives, and the Culm operator	91
3.10	The At, Before, and After operators	96
3.11	The Fills operator	101
3.12	The Begin and End operators	102
3.13	The Ntense operator	103
3.14	The For operator	105
3.15	The Perf operator	107
3.16	Occurrence identifiers	111
3.17	Tense anaphora and localisation time	115
3.18	Expressing habituais	115
3.19	Summary	117
4	From English to TOP	118
4.1	Introduction	118
4.2	HPSG basics	118
4.2.1	Lexical signs and sort hierarchy	119
4.2.2	Lexical rules	121
4.2.3	Schemata and principles	121
4.3	Representing TOP yes/no formulae in HPSG	121
4.4	More on the subsorts of ind	124
4.5	Representing TOP quantifiers in HPSG	128
4.6	Extracting TOP formulae from HPSG signs	130

4.7	Verb forms	131
4.7.1	Single-word verb forms	131
4.7.2	Auxiliary verbs and multi-word verb forms	136
4.8	Predicative and non-predicative prepositions	142
4.8.1	Predicative prepositions	142
4.8.2	Non-predicative prepositions	144
4.9	Nouns	145
4.9.1	Non-predicative nouns	146
4.9.2	Predicative nouns	152
4.10	Adjectives	157
4.11	Temporal adverbials	161
4.11.1	Punctual adverbials	161
4.11.2	Period adverbials	166
4.11.3	Duration adverbials	168
4.12	Temporal complements of habituais	171
4.13	Fronted temporal modifiers	175
4.14	Temporal subordinate clauses	176
4.15	Interrogatives	178
4.16	Multiple temporal modifiers	182
4.17	Post-processing	186
4.18	Summary	189
5	From TOP to TSQL2	191
5.1	Introduction	191
5.2	An introduction to TSQL2	191
5.2.1	The traditional relational model	192
5.2.2	TSQL2's model of time	193
5.2.3	BCDM	195
5.2.4	The TSQL2 language	198
5.3	Modifications of TSQL2	205
5.3.1	Referring to attributes by number	205

5.3.2	(SUBPERIOD) and (NOSUBPERIOD)	206
5.3.3	Calendric relations	208
5.3.4	The INTERVAL function	210
5.3.5	Correlation names used in the same FROM clause where they are defined	211
5.3.6	Equality checks and different domains	212
5.3.7	Other minor changes	213
5.4	Additional TSQL2 terminology	213
5.5	Modifications in TOP and additional TOP terminology	217
5.6	Linking the TOP model to the database	219
5.7	The h functions	221
5.8	The TOP model in terms of database concepts	223
5.9	The h' functions	225
5.10	Formulation of the translation problem	230
5.11	The translation rules	234
5.12	Optimising the generated TSQL2 code	244
5.13	Related work	246
5.14	Summary	248
6	The prototype NLITDB	250
6.1	Introduction	250
6.2	Architecture of the prototype NLITDB	250
6.3	The grammar and parser	251
6.4	The extractor of TOP formulae and the post-processor	253
6.5	The TOP to TSQL2 translator	253
6.6	Modules to be added	255
6.6.1	Preprocessor	256
6.6.2	Quantifier scoping	258
6.6.3	Anaphora resolution	259
6.6.4	Equivalential translator	259
6.6.5	Response generator	262

6.6.6	Configuration tools	262
6.7	The airport database	263
6.8	Sample questions and output	265
6.9	Speed issues	284
6.10	Summary	285
7	Comparison with Previous Work on NLITDBs	286
7.1	Previous work on NLITDBs	286
7.1.1	Clifford	286
7.1.2	Bruce	289
7.1.3	De, Pan, and Whinston	290
7.1.4	Moens	291
7.1.5	Spenceley	293
7.1.6	Brown	294
7.1.7	Other related work	295
7.2	Assessment	296
7.2.1	English temporal mechanisms and their semantics	297
7.2.2	Intermediate representation language	298
7.2.3	Mapping from English to representation language	299
7.2.4	Mapping from representation language to database language	299
7.2.5	Temporal database model and language	299
7.2.6	Implementation	300
7.3	Summary	300
8	Conclusions	302
8.1	Summary of this thesis	302
8.2	Further work	303
	Bibliography	306
	Appendix	320
A	Translation rules and proofs for chapter 5	320

A.1	Introduction	320
A.2	Lemmata	321
A.3	Translation rules for yes/no formulae and proof of theorem 5.2	323
A.3.1	$\pi(\tau_1, \dots, \tau_n)$	324
A.3.2	$Culm[\pi(\tau_1, \dots, \tau_n)]$	328
A.3.3	$\phi_1 \wedge \phi_2$	333
A.3.4	$Pres[\phi']$	337
A.3.5	$Past[\beta, \phi']$	339
A.3.6	$Perf[\beta, \phi']$	342
A.3.7	$Ntense[\beta, \phi']$	347
A.3.8	$Ntense[now^*, \phi']$	347
A.3.9	$For[\sigma_c, \nu_{qty}, \phi']$	348
A.3.10	$Begin[\phi']$	350
A.3.11	$End[\phi']$	355
A.3.12	$At[\kappa, \phi']$	356
A.3.13	$Before[\kappa, \phi']$	358
A.3.14	$After[\kappa, \phi']$	358
A.3.15	$At[\sigma_g, \beta, \phi']$	359
A.3.16	$Before[\sigma_g, \beta, \phi']$	363
A.3.17	$After[\sigma_g, \beta, \phi']$	364
A.3.18	$At[\sigma_c, \beta, \phi']$	364
A.3.19	$Before[\sigma_c, \beta, \phi']$	365
A.3.20	$After[\sigma_c, \beta, \phi']$	365
A.3.21	$At[\phi_1, \phi_2]$	366
A.3.22	$Before[\phi_1, \phi_2]$	373
A.3.23	$After[\phi_1, \phi_2]$	374
A.4	Translation rules for wh-formulae and proof of theorem 5.1	375
A.4.1	$? \beta_1 ? \beta_2 ? \beta_3 \dots ? \beta_n \phi'$	375
A.4.2	$?_{maxl} \beta_1 ? \beta_2 ? \beta_3 \dots ? \beta_n \phi'$	379

List of Tables

2.1	Verbs of the airport domain	26
2.2	Punctual adverbials in the framework of this thesis	44
2.3	Period adverbials in the framework of this thesis	49
2.4	Duration “ <i>for</i> . . . ” adverbials in the framework of this thesis	52
2.5	Duration “ <i>in</i> . . . ” adverbials in the framework of this thesis	54
2.6	Periods of “ <i>while</i> . . . ” clauses in the framework of this thesis	56
2.7	Boundaries of “ <i>before</i> . . . ” clauses in the framework of this thesis . . .	59
2.8	Boundaries of “ <i>after</i> . . . ” clauses in the framework of this thesis	60
2.9	The linguistic coverage of the framework of this thesis	72

List of Figures

1.1	Abstract architecture of many modern NLIDBs	3
2.1	Determining the aspectual class of a verb's base form	21
3.1	"Is BA737 at gate 2?"	88
3.2	"Was J.Adams inspecting BA737?" vs. "Did J.Adams inspect BA737?"	92
3.3	A flawed Prog operator	96
3.4	The Perf operator	107
3.5	First reading of "J.Adams had inspected gate 2 on 27/9/95"	109
3.6	Second reading of "J.Adams had inspected gate 2 on 27/9/95"	110
3.7	Occurrence identifiers	112
4.1	Subsorts of <i>psoa</i>	122
4.2	Subsorts of <i>operator</i>	123
4.3	<i>ind</i> and its subsorts – simplified version	124
4.4	<i>partng</i> , <i>ind</i> , and their subsorts	126
5.1	Paths from basic TOP expressions to the modelled world	219
5.2	Paths from TOP formulae to their denotations	220
5.3	Example of generated TSQL2 code	244
5.4	Shortened TSQL2 code	246
6.1	Architecture of the prototype NLITDB	251
6.2	Extended architecture of the prototype NLITDB	255
6.3	Relations of the airport database	263

Index of Symbols

Page numbers point to the definitions of the symbols. Symbols followed by “()” are names of functions. Symbols followed by “[]” are TOP operators. Only the new HPSG symbols of this thesis (excluding domain-dependent ones) are listed. Consult the appendix of [Pollard & Sag 94] for other HPSG symbols.

$\lceil \rceil$ (corners)	218
• (SUL operator, previous time-point)	246
◦ (SUL operator, next time-point)	246
\prec (precedes)	79
\diamond (SUL’s past operator)	246
\sqsubset (proper subperiod)	81
\sqsubseteq (subperiod)	81
? (TOP’s interrogative quantifier)	78, 86
? _{maxl} (TOP’s interrogative-maximal quantifier)	78, 86
\wedge (TOP’s conjunction)	76, 84
<i>activity</i> (HPSG sort, activity aspectual class)	120
<i>AFORMS</i> (set of all TOP atomic formulae)	75
<i>After</i> [] (used to express “after”)	76, 99
<i>after_op</i> (HPSG sort, corresponds to TOP’s <i>After</i>)	122
AND (TSQL2’s conjunction)	199
<i>and</i> (HPSG sort, corresponds to TOP’s conjunction)	122
ARG1, 2, 3 (new HPSG features, correspond to TOP predicate arguments)	122
AS (TSQL2 keyword, introduces correlation names)	199
ASPECT (HPSG feature)	120, 163
<i>At</i> [] (narrows the localisation time)	76, 96
<i>at_op</i> (HPSG sort, corresponds to TOP’s <i>At</i>)	122
<i>Before</i> [] (used to express “before”)	76, 99
<i>before_op</i> (HPSG sort, corresponds to TOP’s <i>Before</i>)	122
<i>Begin</i> [] (used to refer to start-points of situations)	76, 102
BEGIN (TSQL2 keyword, returns the start-point of a temporal element)	200
<i>begin</i> (HPSG sort, corresponds to TOP’s <i>Begin</i>)	122
<i>CHRONS</i> (set of all chronons)	194
<i>cnsq_state</i> (HPSG sort, consequent state)	120
<i>coalesce</i> () (effect of (ELEMENT))	204
<i>compl_partng</i> (HPSG sort, represents TOP complete partitioning names)	127
CONJUNCT1, 2 (HPSG features, used in the representation of TOP formulae)	122
CONS (set of all TOP constants)	74
CONTAINS (TSQL2 keyword, checks if a chronon belongs to a set of chronons)	202
<i>CPARTS</i> (set of all TOP complete partitioning names)	75
<i>Culm</i> [] (used to express non-progressives of culminating activity verbs)	76, 93
<i>culm</i> (HPSG sort, corresponds to TOP’s <i>Culm</i>)	122
<i>culmact</i> (HPSG sort, culminating activity)	120

D (universal domain)	192
$D(A)$ (domain of the attribute A)	192
\mathcal{D}_A (set of all attributes)	192
\mathcal{D}_D (set of all domains)	192
DISTINCT (TSQL2 keyword, removes duplicate tuples)	199
D_P (set of all attribute values that denote periods)	197
D_P^* ($D_P \cup \emptyset$)	198
D_T (set of all attribute values that denote temporal elements)	195
DURATION (HPSG feature, used in the representation of TOP formulae)	122
DUR_UNIT (HPSG feature, used in the representation of TOP formulae)	122
(ELEMENT) (TSQL2 partitioning unit)	203
$End[]$ (used to refer to end-points of situations)	76, 103
END (TSQL2 keyword, returns the end-point of a temporal element)	200
end (HPSG sort, corresponds to TOP's End)	122
$error$ (signals evaluation error)	216
et (event time)	84
ET_HANDLE (HPSG feature, used in the representation of TOP formulae)	122
$eval()$ (evaluates TSQL2 expressions)	216
$FCN(\xi)$ (set of all correlation names with free column references in ξ)	215
$f_{cons}()$ (maps TOP constants to world objects)	82, 224
$f_{cparts}()$ (assigns complete partitionings to elements of $CPARTS$)	83, 225
$f_{culms}()$ (shows if the situation of a predicate reaches its climax)	82, 225
$f_D()$ (maps attribute values to world objects)	193
$f_{gparts}()$ (assigns gappy partitionings to elements of $GPARTS$)	83, 225
$Fills[]$ (requires $et = lt$)	76, 102
$For[]$ (used to express durations)	76, 105
FORMS (set of all TOP formulae)	79
for_op (HPSG sort, corresponds to TOP's For)	122
$f_{pfuns}()$ (returns the maximal periods where predicates hold)	82, 224
FROM (TSQL2 keyword, shows the relations on which a SELECT operates)	198
G, G_M (set of all variable assignments)	83
$g(), g_o^\beta()$ (variable assignment)	83
$gappy_partng$ (HPSG sort, represents TOP gappy part. names and some terms) ...	127
G^{db} (set of all assignments to correlation names)	216
$g^{db}(), (g^{db})_{\langle v_1, v_2, \dots \rangle}^\alpha()$ (assignment to correlation names)	216
$GPARTS$ (set of all TOP gappy partitioning names)	75
$h_{cons}()$ (TOP constants to attribute values)	221, 226
$h'_{cons}()$ (similar to h_{cons} but returns TSQL2 expressions)	226
$h_{cparts}()$ (compl. part. names to relations representing compl. partitionings) ..	223, 229
$h'_{cparts}()$ (similar to h_{cparts} but returns TSQL2 expressions)	229
$h_{culms}()$ (predicates to relations showing if situations reach their climaxes) ..	222, 227
$h'_{culms}()$ (similar to h_{culms} but returns TOP expressions)	227
$h_{gparts}()$ (gappy part. names to relations representing gappy partitionings) ..	222, 229
$h'_{gparts}()$ (similar to h_{gparts} but returns TSQL2 expressions)	229
$h_{pfuns}()$ (predicates to relations showing maximal periods of situations)	221, 226

$h'_{pfuns}()$ (similar to h_{pfuns} but returns TSQL2 expressions)	226
(INSTANT) (TSQL2 partitioning unit)	203
INSTANTS (set of all instantaneous periods)	80, 194
INSTANTS _{⟨PTS, <⟩} (set of all instantaneous periods over ⟨PTS, <⟩)	80
INSTANTS _{⟨CHRONs, <^{db}⟩} (set of all instantaneous periods over ⟨CHRONs, < ^{db} ⟩) ..	194
interp() (interpretation of resulting relation)	230
interrog (HPSG sort, represents TOP interrogative quantifiers)	129
interrog_maxl (HPSG sort, represents TOP interrogative-maximal quantifiers)	129
INTERSECT (TSQL2 keyword, computes the intersection of two sets of chronons) ...	202
INTERVAL (TSQL2 keyword, returns intervals or introduces interval literals) ...	200, 210
lex_state (HPSG sort, lexical state)	120
lt (localisation time)	84
MAIN_PSOA (HPSG feature, used in the representation of TOP formulae)	122
maxpt() (latest time-point in a set)	81
minpt() (earliest time-point in a set)	81
maxlpers() (maximal periods of a set or temporal element)	81, 194
next() (next time-point)	80
non_temp_ent (HPSG sort, represents non-temporal entities)	124
nosubperiod() (effect of (NOSUBPERIOD))	208
(NOSUBPERIOD) (TSQL2 partitioning unit)	208
now (HPSG sort, represents TOP's now*)	125
Ntense[] (used when expressing nouns or adjectives)	76, 104
ntense (HPSG sort, corresponds to TOP's Ntense)	122
NVREL _P ("normalised" elements of VREL _P)	198
NVREL _P (n) (set of all relations in VREL _P with n explicit attributes)	198
ω (operator of Clifford's algebra)	289
OBJS (TOP's world objects)	81
OBJS ^{db} (BCDM's world objects)	193
(OBJS) ⁿ (OBJS × ⋯ × OBJS)	82
occur_var (HPSG sort, represents occurrence identifiers)	122
operator (HPSG sort, represents TOP operators)	122
other_temp_ent_var (HPSG sort, represents some time-denoting TOP variables) ...	125
Part[] (used to select periods from partitionings)	76, 84, 85
part (HPSG sort, corresponds to TOP's Part)	122
PARTNG (HPSG feature, used in the representation of TOP formulae)	122
partng (HPSG sort, represents TOP partitioning names)	127
PARTS (set of all TOP partitioning names)	75
PART_VAR (HPSG feature, used in the representation of TOP formulae)	122
Past[] (used to refer to the past)	76, 91
past (HPSG sort, corresponds to TOP's Past)	122
pcoalesce() (effect of (PERIOD))	205
Perf[] (used to express the past perfect)	76, 107
perf (HPSG sort, corresponds to TOP's Perf)	122
PERIOD (TSQL2 keyword, constructs periods or introduces period literals)	200

(PERIOD) (TSQL2 partitioning unit)	204
<i>PERIODS</i> (set of all periods)	80, 194
<i>PERIODS*</i> (<i>PERIODS</i> $\cup \emptyset$)	80, 194
<i>PERIODS</i> _{$\langle PTS, \prec \rangle$} (set of all periods over $\langle PTS, \prec \rangle$)	80
<i>PERIODS</i> _{$\langle CHRONs, \prec^{db} \rangle$} (set of all periods over $\langle CHRONs, \prec^{db} \rangle$)	194
<i>PFUNS</i> (set of all TOP predicate functors)	75
<i>point</i> (HPSG sort, point aspectual class)	120
<i>pow()</i> (powerset)	82
PRECEDES (TSQL2 keyword, checks temporal precedence)	202
<i>predicate</i> (HPSG sort, represents TOP predicates)	122
<i>Pres[]</i> (used to refer to the present)	76, 88
<i>pres</i> (HPSG sort, corresponds to TOP's <i>Pres</i>)	122
<i>prev()</i> (previous time-point)	80
<i>progressive</i> (HPSG sort, progressive state)	120
<i>PTS</i> (set of all time-points)	79
SELECT (TSQL2 keyword, introduces a TSQL2 query)	198
<i>sem_num</i> (HPSG sort, represents numbers)	125
since (SUL operator)	246
SNAPSHOT (TSQL2 keyword, signals that a snapshot relation is to be created)	200
<i>SREL</i> (set of all snapshot relations)	198
<i>SREL</i> (<i>n</i>) (set of all snapshot relations of <i>n</i> attributes)	198
<i>st</i> (speech time)	84
<i>state</i> (HPSG sort, state aspectual class)	120
<i>subperiod()</i> (effect of (SUBPERIOD))	206
(SUBPERIOD) (TSQL2 partitioning unit)	206
σ - WHEN (operator of Clifford's algebra)	289
<i>TELEMS</i> (set of all temporal elements)	194
<i>TELEMS</i> _{$\langle CHRONs, \prec^{db} \rangle$} (set of all temporal elements over $\langle CHRONs, \prec^{db} \rangle$)	194
<i>temp_ent</i> (HPSG sort, represents temporal entities)	124
<i>TERMS</i> (set of all TOP terms)	74
<i>t_{first}</i> (earliest time-point)	80
TIME_SPEC (HPSG feature, used in the representation of TOP formulae)	122
TIMESTAMP (TSQL2 keyword, introduces chronon-denoting literals)	200
<i>t_{last}</i> (latest time-point)	80
<i>tr()</i> (TOP to TSQL2 mapping)	230
<i>trans()</i> (auxiliary TOP to TSQL2 mapping)	230
TVAR (HPSG feature, shows if an index represent a TOP variable or not)	125, 128
TVAR (HPSG feature, shows if an index represents a TOP variable)	123
until (SUL operator)	246
VALID (TSQL2 keyword, refers to time-stamps of tuples)	200
<i>VARs</i> (set of all TOP variables)	74
<i>v_{ϵ}</i> (attribute value denoting \emptyset)	198
<i>VREL_P</i> (set of all valid time relations time-stamped by elements of <i>D_P</i>)	198
<i>VREL_P</i> (<i>n</i>) (relations in <i>VREL_P</i> with <i>n</i> explicit attributes)	198
WHERE (TSQL2 keyword, introduces restrictions)	198

<i>WHFORMS</i> (set of all TOP wh-formulae).....	78
<i>WHFORMS</i> ₁ (set of all TOP wh-formulae with no $?_{mxl}$)	78
<i>WHFORMS</i> ₂ (set of all TOP wh-formulae with a $?_{mxl}$).....	78
<i>YNFORMS</i> (set of all TOP yes/no formulae).....	76

Chapter 1

Introduction

“No time like the present.”

1.1 Subject of this thesis

Over the past thirty years, there have been significant advances in the area of natural language interfaces to databases (NLIDBs). NLIDBs allow users to access information stored in databases by typing requests expressed in natural language (e.g. English). (The reader is referred to [Perrault & Grosz 88], [Copestake & Sparck Jones 90], and [Androutsopoulos *et al.* 95b] for surveys of NLIDBs.¹) Most of the existing NLIDBs were designed to interface to “snapshot” database systems, that provide very limited facilities for manipulating time-dependent data. Consequently, most NLIDBs also provide very limited support for the notion of time. In particular, they were designed to answer questions that refer mainly to the present (e.g. (1.1) – (1.3)), and do not support adequately the mechanisms that natural language uses to express time. For example, very few (if any) temporal adverbials (“*in 1991*”, “*after 5:00pm*”, etc.) and verb forms (simple past, past continuous, past perfect, etc.) are typically allowed, and their semantics are usually over-simplified or ignored.

(1.1) What is the salary of each engineer?

(1.2) Who is at site 4?

(1.3) Which generators are in operation?

¹ The project described in this thesis began with an extensive survey of NLIDBs. The results of this survey were reported in [Androutsopoulos *et al.* 95b].

The database community is becoming increasingly interested in *temporal* database systems. These are intended to store and manipulate in a principled manner information not only about the present, but also about the past and the future (see [Tansel *et al.* 93] and [Jensen *et al.* 93] for an introduction, and [Bolour *et al.* 83], [McKenzie 86], [Stam & Snodgrass 88], [Soo 91], [Kline 93], and [Tsotras & Kumar 96] for bibliographies). When interfacing to temporal databases, it becomes crucial for NLIDBs to interpret correctly the temporal linguistic mechanisms (verb tenses, temporal adverbials, temporal subordinate clauses, etc.) of questions like (1.4) – (1.6).

- (1.4) What was the salary of each engineer while ScotCorp was building bridge 5?
- (1.5) Did anybody leave site 4 before the chief engineer had inspected the control room?
- (1.6) Which systems did the chief engineer inspect on Monday after the auxiliary generator was in operation?

In chapter 7, I argue that previous approaches to natural language interfaces for *temporal* databases (NLITDBs) are problematic, mainly because they ignore important time-related linguistic phenomena, and/or they assume idiosyncratic temporal database systems. This thesis develops a principled framework for constructing English NLITDBs, drawing on research in linguistic theories of time, temporal logics, and temporal databases.

1.2 Some background

This section introduces some ideas from NLIDBs, linguistic theories of time, temporal logics, and temporal databases. Ideas from the four areas will be discussed further in following chapters.

1.2.1 Natural language interfaces to databases

Past work on NLIDBs has shown the benefits of using the abstract architecture of figure 1.1. The natural language question is first parsed and analysed semantically by a linguistic front-end, which translates the question into an intermediate meaning representation language (typically, some form of logic). The generated intermediate language expression captures formally what the system understands to be the meaning of the

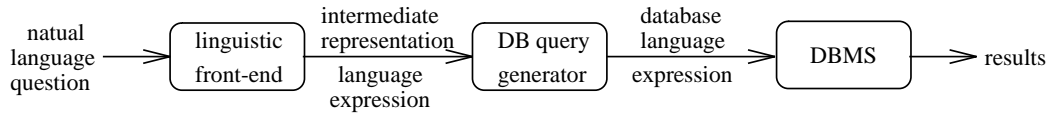


Figure 1.1: Abstract architecture of many modern NLIDBs

natural language question, without referring to particular database constructs. The intermediate language expression is then translated into a database language (usually SQL [Ullman 88] [Melton & Simon 93]) that is supported by the underlying *database management system* (DBMS; this is the part of the database system that manipulates the information in the database). The resulting database language expression specifies what information needs to be retrieved in terms of database constructs. The DBMS retrieves this information by evaluating the database language expression, and the obtained information is reported back to the user.

Most NLIDBs can only handle questions referring to a particular knowledge-domain (e.g. questions about train departures, or about the employees of a company), and need to be configured before they can be used in a new domain. The configuration typically includes “teaching” the NLIDB words that can be used in the new domain, and linking basic expressions of the formal intermediate language to database constructs (see section 6 of [Androutsopoulos *et al.* 95b]).

The architecture of figure 1.1 has proven to have several advantages (see sections 5.4 and 6 of [Androutsopoulos *et al.* 95b]), like modularity (e.g. the linguistic-front end is shielded from database-level issues), and DBMS portability (the same linguistic front-end can be used with DBMSs that support different database languages). This thesis examines how this architecture can be used to construct NLITDBs.

1.2.2 Tense and aspect theories

In English, temporal information can be conveyed by verb forms (simple past, past continuous, present perfect, etc.), nouns (“*beginning*”, “*predecessor*”, “*day*”), adjectives (“*earliest*”, “*next*”, “*annual*”), adverbs (“*yesterday*”, “*twice*”), prepositional phrases (“*at 5:00pm*”, “*for two hours*”), and subordinate clauses (“*while tank 4 was empty*”), to mention just some of the available temporal mechanisms. A linguistic theory of time must account for the ways in which these mechanisms are used (e.g. specify what

is the temporal content of each verb form, how temporal adverbials or subordinate clauses affect the meaning of the overall sentences, etc.). The term “tense and aspect theories” is often used in the literature to refer to theories of this kind. (The precise meanings of “tense” and “aspect” vary from one theory to the other; see [Comrie 76] and [Comrie 85] for some discussion. Consult chapter 5 of [Kamp & Reyle 93] for an extensive introduction to tense and aspect phenomena.)

It is common practice in tense and aspect theories to classify natural language expressions or situations described by natural language expressions into *aspectual classes*. (The term “*Aktionsarten*” is often used to refer to these classes.) Many aspectual classifications are similar to Vendler’s taxonomy [Vendler 67], that distinguishes between *state* verbs, *activity* verbs, *accomplishment* verbs, and *achievement* verbs.² For example, “*to run*” (as in “*John ran.*”) is said to be an activity verb, “*to know*” (as in “*John knows the answer.*”) a state verb, “*to build*” (as in “*John built a house.*”) an accomplishment verb, and “*to find*” (as in “*Mary found the treasure.*”) an achievement verb.

Vendler’s intuition seems to be that activity verbs describe actions or changes in the world. For example, in “*John ran.*” there is a running action in the world. In contrast, state verbs do not refer to any actions or changes. In “*John knows the answer.*” there is no change or action in the world. Accomplishment verbs are similar to activity verbs, in that they denote changes or actions. In the case of accomplishment verbs, however, the action or change has an inherent “climax”, a point that has to be reached for the action or change to be considered complete. In “*build a house*” the climax is the point where the whole of the house has been built. If the building stops before the whole of the house has been built, the building action is incomplete. In contrast, the action of the activity verb “*to run*” (with no object, as in “*John ran.*”) does not seem to have any climax. The runner can stop at any time without the running being any more or less complete. If, however, “*to run*” is used with an object denoting a precise distance (e.g. “*to run a mile*”), then the action *does* have a climax: the point where the runner completes the distance. In this case, “*to run*” is an accomplishment verb. Finally, achievement verbs, like “*to find*”, describe instantaneous events. In “*Mary found the treasure.*” the actual finding is instantaneous (according to Vendler, the time during

² According to Mourelatos [Mourelatos 78], a similar taxonomy was developed independently in [Kenny 63], where Kenny notes that his classification is similar to the distinction between *kineiseis* and *energiai* introduced by Aristotle in *Metaphysics*, Θ.1048b, 18–36.

which Mary was searching for the treasure is not part of the actual finding). In contrast, in “*John built a house.*” (accomplishment verb) the actual building action may have lasted many years.

Aspectual taxonomies are invoked to account for semantic differences in similar sentences. The so-called “imperfective paradox” [Dowty 77] [Lascarides 88] is a well-known example (various versions of the imperfective paradox have been proposed; see [Kent 93]). The paradox is that if the answer to a question like (1.7) is affirmative, then the answer to the non-progressive (1.8) must also be affirmative. In contrast, an affirmative answer to (1.9) does not necessarily imply an affirmative answer to (1.10) (John may have abandoned the repair before completing it). The NLITDB must incorporate some account for this phenomenon. If the NLITDB generates an affirmative response to (1.7), there must be some mechanism to guarantee that the NLITDB’s answer to (1.8) will also be affirmative. No such mechanism is needed in (1.9) and (1.10).

(1.7) Was IBI ever advertising a new computer?

(1.8) Did IBI ever advertise a new computer?

(1.9) Was J.Adams ever repairing engine 2?

(1.10) Did J.Adams ever repair engine 2?

The difference between (1.7) – (1.8) and (1.9) – (1.10) can be accounted for by classifying “*to advertise*” as an activity, “*to repair*” as an accomplishment, and by stipulating that: (i) the simple past of an accomplishment requires the climax to have been reached; (ii) the past continuous of an accomplishment or activity, and the simple past of an activity impose no such requirement. Then, the fact that an affirmative answer to (1.9) does not necessarily imply an affirmative answer to (1.10) is accounted for by the fact that (1.10) requires the repair to have been completed, while (1.9) merely requires the repair to have been ongoing at some past time. In contrast (1.8) does not require any climax to have been reached; like (1.7), it simply requires the advertising to have been ongoing at some past time. Hence, an affirmative answer to (1.7) implies an affirmative answer to (1.8). It will become clear in chapter 2 that aspectual taxonomies pertain to the semantics of almost all temporal linguistic mechanisms.

1.2.3 Temporal logics

Time is an important research topic in logic, and many formal languages have been proposed to express temporal information [vanBenthem 83] [Gabbay *et al.* 94]. One of the simplest approaches is to use the traditional first-order predicate logic, introducing time as an extra argument of each predicate. (1.11) would be represented as (1.12), where t is a time-denoting variable, \prec stands for temporal precedence, \sqsubseteq for temporal inclusion, and *now* is a special term denoting the present moment. The answer to (1.11) would be affirmative iff (1.12) evaluates to true, i.e. iff there is a time t , such that t precedes the present moment, t falls within 1/10/95, and tank 2 contained water at t . (Throughout this thesis, I use “iff” as a shorthand for “if and only if”.)

(1.11) Did tank 2 contain water (some time) on 1/10/95?

(1.12) $\exists t \text{ contain}(\text{tank2}, \text{water}, t) \wedge t \prec \text{now} \wedge t \sqsubseteq 1/10/95$

An alternative approach is to employ *temporal operators*, like Prior’s P (past) and F (future) [Prior 67]. In that approach, formulae are evaluated with respect to particular times. For example, $\text{contain}(\text{tank2}, \text{water})$ would be true at a time t iff tank 2 contained water at t . Assuming that ϕ is a formula, $P\phi$ is true at a time t iff there is a time t' , such that t' precedes t , and ϕ is true at t' . Similarly, $F\phi$ is true at t iff there is a t' , such that t' follows t , and ϕ is true at t' . “Tank 2 contains water.” can be expressed as $\text{contain}(\text{tank2}, \text{water})$, “Tank 2 contained water.” as $P \text{contain}(\text{tank2}, \text{water})$, “Tank 2 will contain water.” as $F \text{contain}(\text{tank2}, \text{water})$, and “Tank 2 will have contained water.” as $F P \text{contain}(\text{tank2}, \text{water})$. Additional operators can be introduced, to capture the semantics of temporal adverbials, temporal subordinate clauses, etc. For example, an *On* operator could be introduced, with the following semantics: if ϕ is a formula and κ specifies a day (e.g. the day 1/10/95), then $\text{On}[\kappa, \phi]$ is true at a time t iff t falls within the day specified by κ , and ϕ is true at t . Then, (1.11) could be represented as (1.13).

(1.13) $P \text{ On}[1/10/95, \text{contains}(\text{tank2}, \text{water})]$

The intermediate representation language of this thesis, called TOP, adopts the operators approach (TOP stands for “language with Temporal OPERators”). Temporal operators have also been used in [Dowty 82], [Lascarides 88], [Richards *et al.* 89], [Kent 93], [Crouch & Pulman 93], [Pratt & Bree 95], and elsewhere.

Unlike logics designed to be used in systems that reason about what changes or remains the same over time, what can or will happen, what could or would have happened, or how newly arrived information fits within already known facts or assumptions (e.g. the situation calculus of [McCarthy & Hayes 69], the event calculus of [Kowalski & Sergot 86], and the logics of [Allen 83], [Allen 84], and [McDermott 82] – see [Vila 94] for a survey), TOP is not intended to be used in reasoning. I provide no inference rules for TOP, and this is why I avoid calling TOP a logic. TOP is only a formal language, designed to facilitate the systematic mapping of temporal English questions to formal expressions (this mapping is not a primary consideration in the above mentioned logics). The answers to the English questions are not generated by carrying out reasoning in TOP, but by translating the TOP expressions to database language expressions, which are then evaluated by the underlying DBMS. The definition of TOP will be given in chapter 3, where other ideas from temporal logics will also be discussed.

1.2.4 Temporal databases

In the *relational model* [Codd 70], currently the dominant database model, information is stored in *relations*. Intuitively, relations can be thought of as tables, consisting of rows (called *tuples*) and columns (called *attributes*). For example, the *salaries* relation below shows the present salaries of the current employees of a company. In the case of *salaries*, whenever the salary of an employee is changed, or whenever an employee leaves the company, the corresponding tuple is modified or deleted. Hence, the database “forgets” past facts, and does not contain enough information to answer questions like “What was the salary of T.Smith on 1/1/1992?”.

<i>salaries</i>	
<i>employee</i>	<i>salary</i>
<i>J.Adams</i>	17000
<i>T.Smith</i>	19000
...	...

It is certainly true that traditional database models and languages *can* and *have* been used to store temporal information. (This has led several researchers to question the need for special temporal support in database systems; see [Davies *et al.* 95] for some discussion.) For example, two extra attributes (*from* and *to*) could be added to *salaries* (as in *salaries2*) to *time-stamp* its tuples, i.e. to show when each employee had the corresponding salary.

<i>salaries2</i>			
<i>employee</i>	<i>salary</i>	<i>from</i>	<i>to</i>
<i>J.Adams</i>	17000	1/1/88	5/5/90
<i>J.Adams</i>	18000	6/5/90	9/8/91
<i>J.Adams</i>	21000	10/8/91	27/3/93
...
<i>T.Smith</i>	17000	1/1/89	1/10/90
<i>T.Smith</i>	21000	2/10/90	23/5/92
...

The lack of special temporal support in traditional database models and languages, however, complicates the task of expressing in database language time-related data manipulations. We may want, for example, to compute from *salaries2* a new relation *same_salaries* that shows the times when J.Adams and T.Smith had the same salary, along with their common salary:

<i>same_salaries</i>		
<i>salary</i>	<i>from</i>	<i>to</i>
17000	1/1/89	5/5/90
21000	10/8/91	23/5/92
...

That is, for every tuple of J.Adams in *salaries2*, we need to check if the period specified by the *from* and *to* values of that tuple overlaps the period specified by the *from* and *to* values of a tuple for T.Smith which has the same *salary* value. If they overlap, we need to compute the intersection of the two periods. This cannot be achieved easily in the present version of SQL (the dominant database language for relational databases [Ullman 88] [Melton & Simon 93]), because SQL currently does not have any special commands to check if two periods overlap, or to compute the intersection of two periods (in fact, it does not even have a period datatype).

As a further example, the approach of adding a *from* and a *to* attribute to every relation allows relations like *rel1* and *rel2* to be formed. Although *rel1* and *rel2* contain different tuples, they represent the same information.

<i>rel1</i>			
<i>employee</i>	<i>salary</i>	<i>from</i>	<i>to</i>
<i>G.Foot</i>	17000	1/1/88	9/5/88
<i>G.Foot</i>	17000	10/5/88	9/5/93
<i>G.Foot</i>	18000	10/5/93	1/3/94
<i>G.Foot</i>	18000	2/3/94	11/2/95
<i>G.Foot</i>	17000	12/2/95	31/3/96

<i>rel2</i>			
<i>employee</i>	<i>salary</i>	<i>from</i>	<i>to</i>
<i>G.Foot</i>	17000	1/1/88	31/5/89
<i>G.Foot</i>	17000	1/6/89	10/8/92
<i>G.Foot</i>	17000	11/8/92	9/5/93
<i>G.Foot</i>	18000	10/5/93	11/2/95
<i>G.Foot</i>	17000	12/2/95	31/3/96

Checking if the two relations represent the same information is not easy in the current SQL version. This task would be greatly simplified if SQL provided some mechanism to “normalise” relations, by merging tuples that apart from their *from* and *to* values are identical (tuples of this kind are called *value-equivalent*). In our example, that mechanism would turn both *rel1* and *rel2* into *rel3*. To check that *rel1* and *rel2* contain the same information, one would check that the normalised forms of the two relations are the same.

<i>rel3</i>			
<i>employee</i>	<i>salary</i>	<i>from</i>	<i>to</i>
<i>G.Foot</i>	17000	1/1/88	9/5/93
<i>G.Foot</i>	18000	10/5/93	11/2/96
<i>G.Foot</i>	17000	12/2/95	31/3/96

Numerous temporal versions of SQL and the relational model have been proposed (e.g. [Clifford & Warren 83], [Ariav 86], [Tansel 86], [Snodgrass 87], [Navathe & Ahmed 88], [Gadia 88], [Lorentzos & Johnson 88]; see [McKenzie & Snodgrass 91] for a summary of some of the proposals). These add special temporal facilities to SQL (e.g. predicates to check if two periods overlap, functions to compute intersections of periods, etc.), and often special types of relations to store time-varying information (e.g. relations that force value-equivalent tuples to be merged automatically). Until recently there was little consensus on how temporal support should be added to SQL and the relational model (or other database languages and models), with every researcher in the field adopting his/her own temporal database language and model. Perhaps as a result of this, very few temporal DBMSs have been implemented (these are mostly early prototypes; see [Boehlen 95]).

This thesis adopts TSQL2, a recently proposed temporal extension of SQL-92 that was designed by a committee comprising most leading temporal database researchers. (SQL-92 is the latest SQL standard [Melton & Simon 93]. TSQL2 is defined in [Snodgrass 95]. An earlier definition of TSQL2 can be found in [Snodgrass *et al.* 94a].) TSQL2 and the version of the relational model on which TSQL2 is based will be presented in chapter 5, along with some modifications that were introduced to them for the purposes of this thesis. Until recently, there was no implemented DBMS supporting TSQL2. A prototype system, however, which is capable of evaluating TSQL2 queries now exists. (This system is called TIMEDB. See [Boehlen 95] for a brief technical description of TIMEDB. TIMEDB actually supports ATSQL2, a variant of TSQL2. See [Boehlen *et al.* 96] for some information on ATSQL2.)

Researchers in temporal databases distinguish between *valid time* and *transaction time*.³ The valid time of some information is the time when that information was true in the *world*. The transaction time of some information is the time when the *database* “believed” some piece of information. In this thesis, I ignore the transaction-time dimension. I assume that the natural language questions will always refer to the information that the database currently believes to be true. Questions like (1.14), where “on 2/1/95” specifies a transaction time other than the present, will not be considered.

(1.14) According to what the database believed on 2/1/95, what was the salary of J.Adams on 1/1/89?

1.3 Contribution of this thesis

As mentioned in section 1.1, most existing NLIDBs were designed to interface to snapshot database systems. Although there have been some proposals on how to build NLIDBs for temporal databases, in chapter 7 I argue that these proposals suffer from one or more of the following: (i) they ignore important English temporal mechanisms, or assign to them over-simplified semantics, (ii) they lack clearly defined meaning representation languages, (iii) they do not provide complete descriptions of the mappings from natural language to meaning representation language, or (iv) from meaning representation language to database language, (v) they adopt idiosyncratic and often not well-defined temporal database models or languages, (vi) they do not demonstrate that their ideas are implementable. In this thesis, I develop a principled framework for constructing English NLITDBs, attempting to avoid pitfalls (i) – (vi). Building on the architecture of figure 1.1:

- I explore temporal linguistic phenomena that are likely to appear in English questions to NLITDBs. Drawing on existing linguistic theories of time, I formulate an account for many of these phenomena that is simple enough to be embodied in practical NLITDBs.
- Exploiting ideas from temporal logics, I define a temporal meaning representation language (TOP), which I use to represent the semantics of English questions.

³ I adopt the consensus terminology of [Jensen *et al.* 93]. A third term, *user-defined time*, is also employed in the literature to refer to temporal information that is stored in the database without the DBMS treating it in any special way.

- I show how HPSG [Pollard & Sag 87] [Pollard & Sag 94], currently a highly regarded linguistic theory, can be modified to incorporate the tense and aspect account of this thesis, and to map a wide range of English questions involving time to appropriate TOP expressions.
- I present and prove the correctness of a mapping that translates TOP expressions to TSQL2 queries.

This way, I establish a sound route from English questions involving time to a general-purpose temporal database language, that can act as a principled framework for constructing NLITDBs. To ensure that this framework is workable:

- I demonstrate how it can be employed to implement a prototype NLITDB, using the ALE grammar development system [Carpenter 92] [Carpenter & Penn 94] and Prolog [Clocksin & Mellish 94] [Sterling & Shapiro 94]. I configure the prototype NLITDB for a hypothetical air traffic control domain, similar to that of [Sripada *et al.* 94].

Unfortunately, during most of the work of this thesis no DBMS supported TSQL2. As mentioned in section 1.2.4, a prototype DBMS (TIMEDB) that supports a version of TSQL2 (ATSQL2) was announced recently. Although it would be obviously very interesting to link the NLITDB of this thesis to TIMEDB, there is currently very little documentation on TIMEDB. The task of linking the two systems is further complicated by the fact that both adopt their own versions of TSQL2 (TIMEDB supports ATSQL2, and the NLITDB of this thesis adopts a slightly modified version of TSQL2, to be discussed in chapter 5). One would have to bridge the differences between the two TSQL2 versions. Due to shortage of time, I made no attempt to link the NLITDB of this thesis to TIMEDB. The TSQL2 queries generated by the NLITDB are currently not executed, and hence no answers are produced.

Although several issues (summarised in section 8.2) remain to be addressed, I am confident that this thesis will prove valuable to both those wishing to implement NLITDBs for practical applications, and those wishing to carry out further research on NLITDBs, because: (a) it is essentially the first in-depth exploration of time-related problems the NLITDB designer has to face, from the linguistic level down to the database level, (b) it proposes a clearly defined framework for building NLITDBs that addresses a great

number of these problems, and (c) it shows how this framework was used to implement a prototype NLITDB on which more elaborate NLITDBs can be based.

Finally, I note that: (i) the work of this thesis is one of the first to use TSQL2, and one of the first to generate feedback to the TSQL2 designers (a number of obscure points and possible improvements in the definition of TSQL2 were revealed during this project; these were reported in [Androutsopoulos *et al.* 95a]); (ii) the prototype NLITDB of this thesis is currently one of the very few NLIDBs (at least among NLIDBs whose grammar is publicly documented) that adopt HPSG.⁴

1.4 Issues that will not be addressed

To allow the work of this thesis to be completed within the available time, the following issues were not considered.

Updates: This thesis focuses on *questions*. Natural language requests to *update* the database (e.g. (1.15)) are not considered (see [Davidson & Kaplan 83] for work on natural language updates.)

(1.15) Replace the salary of T.Smith for the period 1/1/88 to 5/5/90 by 17000.

Assertions like (1.16) will be treated as yes/no questions, i.e. (1.16) will be treated in the same way as (1.17).

(1.16) On 1/1/89 the salary of T.Smith was 17000.

(1.17) Was the salary of T.Smith 17000 on 1/1/89?

Schema evolution: This term refers to cases where the *structure*, not only the *contents*, of the database change over time (new relations are created, old deleted, attributes are added or removed from relations, etc.; see [McKenzie & Snodgrass 90]). Schema evolution is not considered in this thesis. The structure of the database is assumed to be static, although the information in the database may change over time.

⁴ See also [Cercone *et al.* 93]. A version of the HPSG grammar of this thesis, stripped of its temporal mechanisms, was used in [Seldrup 95] to construct a NLIDB for snapshot databases.

Modal questions: Modal questions ask if something could have happened, or could never have happened, or will necessarily happen, or can possibly happen. For example, “*Could T.Smith have been an employee of IBI in 1985?*” does not ask if T.Smith was an IBI employee in 1985, but if it would have been possible for T.Smith to be an IBI employee at that time. Modal questions are not examined in this thesis (see [Mays 86] and [Lowden *et al.* 91b] for related work).

Future questions: A temporal database may contain predictions about the future. At some company, for example, it may have been decided that T.Smith will retire two years from the present, and that J.Adams will replace him. These decisions may have been recorded in the company’s database. In that context, one may want to submit questions referring to the future, like “*When will T.Smith retire?*” or “*Who will replace T.Smith?*”. To simplify the linguistic data that the work of this thesis had to address, future questions were not considered. The database may contain information about the future, but the framework of this thesis does not currently allow this information to be accessed through natural language. Further work could extend the framework of this thesis to handle future questions as well (see section 8.2).

Cooperative responses: In many cases, it is helpful for the user if the NLIDB reports more information than what the question literally asks for. In the dialogue below (from [Johnson 85]), for example, the system has reasoned that the user would be interested to know about the United flight, and has included information about that flight in its answer although this was not requested.

(1.18) Do American Airlines have a night flight to Dallas?

(1.19) No, but United have flight 655.

In other cases, the user’s requests may be based on false presumptions. (1.20), for example, presumes that there is a flight called BA737. If this is not true, it would be useful if the NLIDB could generate a response like (1.21).

(1.20) Does flight BA737 depart at 5:00pm?

(1.21) Flight BA737 does not exist.

The term *cooperative responses* [Kaplan 82] is used to refer to responses like (1.19) and (1.21). The framework of this thesis includes no mechanism to generate cooperative

responses. During the work of this thesis, however, it became clear that such a mechanism is particularly important in questions to NLITDBs, and hence a mechanism of this kind should be added (this will be discussed further in section 8.2).

Anaphora: Pronouns (“*she*”, “*they*”, etc.), possessive determiners (“*his*”, “*their*”), and some noun phrases (“*the project*”, “*these people*”) are used anaphorically, to refer to contextually salient entities. The term *nominal anaphora* is frequently used to refer to this phenomenon (see [Hirst 81] for an overview of nominal anaphora, and [Hobbs 86] for methods that can be used to resolve pronoun anaphora). Verb tenses and other temporal expressions (e.g. “*on Monday*”) are often used in a similar anaphoric manner to refer to contextually salient times (this will be discussed in section 2.12). The term *temporal anaphora* [Partee 84] is used in that case. Apart from a temporal anaphoric phenomenon related to noun phrases like “*the sales manager*” (to be discussed in section 2.11), for which support is provided, the framework of this thesis currently provides no mechanism to resolve anaphoric expressions (i.e. to determine the entities or times these expressions refer to). Words introducing nominal anaphora (e.g. pronouns) are not allowed, and (excluding the phenomenon of section 2.11) temporal anaphoric expressions are treated as denoting any possible referent (e.g. “*on Monday*” is taken to refer to any Monday).

Elliptical sentences: Some NLIDBs allow elliptical questions to be submitted as follow-ups to previous questions (e.g. “*What is the salary of J.Adams?*”, followed by “*His address?*”; see section 4.6 of [Androutsopoulos *et al.* 95b] for more examples). Elliptical questions are not considered in this thesis.

1.5 Outline of the remainder of this thesis

The remainder of this thesis is organised as follows:

Chapter 2 explores English temporal mechanisms, delineating the set of linguistic phenomena that this thesis attempts to support. Drawing on existing ideas from tense and aspect theories, an account for these phenomena is formulated that is suitable to the purposes of this thesis.

Chapter 3 defines formally TOP, discussing how it can be used to represent the se-

mantics of temporal English expressions, and how it relates to other existing temporal representation languages.

Chapter 4 provides a brief introduction to HPSG, and discusses how HPSG can be modified to incorporate the tense and aspect account of this thesis, and to map English questions involving time to appropriate TOP expressions.

Chapter 5 defines the mapping from TOP to TSQL2, and proves its correctness (parts of this proof are given in appendix A). It also discusses the modifications to TSQL2 that are adopted in this thesis.

Chapter 6 describes the architecture of the prototype NLITDB, provides information about its implementation, and explains which additional modules would have to be added if the system were to be used in real-life applications. Several sample English questions directed to a hypothetical temporal database of an airport are shown, discussing the corresponding output of the prototype NLITDB.

Chapter 7 discusses previous proposals in the area of NLITDBs, comparing them to the framework of this thesis.

Chapter 8 summarises and proposes directions for further research.

Chapter 2

The Linguistic Data and an Informal Account

“There is a time for everything.”

2.1 Introduction

This chapter explores how temporal information is conveyed in English, focusing on phenomena that are relevant to NLITDBS. There is a wealth of temporal English mechanisms (e.g. verb tenses, temporal adverbials, temporal adjectives, etc.), and it would be impossible to consider all of those in this thesis. Hence, several English temporal mechanisms will be ignored, and simplifying assumptions will be introduced in some of the mechanisms that will be considered. One of the goals of this chapter is to specify exactly which linguistic phenomena this thesis attempts to support. For the phenomena that will be supported, a further goal is to provide an informal account of how they will be treated.

Although this chapter draws on existing tense and aspect theories, I stress that it is in no way an attempt to formulate an improved tense and aspect theory. The aim is more practical: to explore how ideas from existing tense and aspect theories can be integrated into NLITDBS, in a way that leads to provably implementable systems.

2.2 Aspectual taxonomies

As mentioned in section 1.2.2, many tense and aspect theories employ aspectual classifications, which are often similar to Vendler’s distinction between states (e.g. “*to know*”, as in “*John knows the answer.*”), activities (e.g. “*to run*”, as in “*John ran.*”), accomplishments (e.g. “*to build*”, as in “*John built a house.*”), and achievements (e.g. “*to find*”, as in “*Mary found the treasure.*”).

Vendler proposes a number of linguistic tests to determine the aspectual classes of verbs. For example, according to Vendler, activity and accomplishment verbs can appear in the progressive (e.g. “*John is running*”, “*John is building a house*”), while state and achievement verbs cannot (*“*John is knowing the answer.*”, **“Mary is finding the treasure*”). Activity verbs are said to combine felicitously with “*for ...*” adverbials specifying duration (“*John ran for two minutes.*”), but sound odd with “*in ...*” duration adverbials (?“*John ran in two minutes.*”). Accomplishment verbs, in contrast, combine felicitously with “*in ...*” adverbials (“*John built a house in two weeks.*”), but sound odd with “*for ...*” adverbials (?“*John built a house for two weeks.*”). Finally, according to Vendler state verbs combine felicitously with “*for ...*” adverbials (e.g. “*John knew the answer for ten minutes (but then forgot it).*”), while achievement verbs sound odd with “*for ...*” adverbials (?“*Mary found the treasure for two hours.*”).

The exact nature of the objects classified by Vendler is unclear. In most cases, Vendler’s wording suggests that his taxonomy classifies verbs. However, some of his examples (e.g. the fact that “*to run*” with no object is said to be an activity, while “*to run a mile*” is said to be an accomplishment) suggest that the natural language expressions being classified are not always verbs, but sometimes larger syntactic constituents (perhaps verb phrases). In other cases, Vendler’s arguments suggest that the objects being classified are not natural language expressions (e.g. verbs, verb phrases), but world situations denoted by natural language expressions. According to Vendler, “*Are you smoking?*” “asks about an activity”, while “*Do you smoke?*” “asks about a state”. In this case, the terms “activity” and “state” seem to refer to types of situations in the world, rather than types of natural language expressions. (The first question probably asks if somebody is actually smoking at the present moment. The second one has a *habitual* meaning: it asks if somebody has the habit of smoking. Vendler concludes that habits “are also states in our sense”.)

Numerous variants of Vendler’s taxonomy have been proposed. These differ in the number of aspectual classes they assume, the names of the classes, the nature of the objects being classified, and the properties assigned to each class. Vlach [Vlach 93] distinguishes four aspectual classes of sentences, and assumes that there is a parallel fourfold taxonomy of world situations. Moens [Moens 87] distinguishes between “states”, “processes”, “culminated processes”, “culminations”, and “points”, commenting that his taxonomy does not classify real world situations, but ways people use to describe world situations. Parsons [Parsons 89] distinguishes three kinds of “eventualities” (“states”, “activities”, and “events”), treating eventualities as entities in the world. Lascarides [Lascarides 88] classifies propositions (functions from time-periods to truth values), distinguishing between “state”, “process”, and “event” propositions.

2.3 The aspectual taxonomy of this thesis

Four aspectual classes are employed in this thesis: *states*, *activities*, *culminating activities*, and *points*. (Culminating activities and points correspond to Vendler’s “accomplishments” and “achievements” respectively. Similar terms are used in [Moens 87] and [Blackburn *et al.* 94].) These aspectual classes correspond to ways of *viewing world situations* that people seem to use: a situation can be viewed as involving no change or action (state view), as an instantaneous change or action (point view), as a change or action with no climax (activity view), or as a change or action with a climax (culminating activity view). (Throughout this thesis, I use “situation” to refer collectively to elements of the world that other authors call “events”, “processes”, “states”, etc.) Determining which view the speaker has in mind is important to understand what the speaker means. For example, “*Which tanks contained oil?*” is typically uttered with a state view. When an “*at ...*” temporal adverbial (e.g. “*at 5:00pm*”) is attached to a clause uttered with a state view, the speaker typically means that the situation of the clause simply holds at the time of the adverbial. There is normally no implication that the situation starts or stops holding at the time of the adverbial. For example, in “*Which tanks contained oil at 5:00pm?*” there is normally no implication that the tanks must have started or stopped containing oil at 5:00pm. In contrast, “*Who ran to the station?*” is typically uttered with a culminating activity view. In this case, an “*at ...*” adverbial usually specifies the time when the situation starts or is completed. “*Who ran to the station at 5:00pm?*”, for example, probably asks for somebody who

started running to the station or reached it at 5:00pm.

Some linguistic markers seem to signal which view the speaker has in mind. For example, the progressive usually signals a state view (e.g. unlike “*Who ran to the station at 5:00pm?*”, “*Who was running to the station at 5:00pm?*” is typically uttered with a state view; in this case, the running is simply ongoing at 5:00pm, it does not start or finish at 5:00pm). Often, however, there are no such explicit markers. The processes employed in those cases by hearers to determine the speaker’s view are not yet fully understood. In an NLITDB, however, where questions refer to a restricted domain, reasonable guesses can be made by observing that in each domain, each verb tends to be associated mainly with one particular view. Certain agreements about how situations are to be viewed (e.g. that some situations are to be treated as instantaneous – point view) will also have been made during the design of the database. These agreements provide additional information about how the situations of the various verbs are viewed in each domain.

More precisely, the following approach is adopted in this thesis. Whenever the NLITDB is configured for a new application domain, the base form of each verb is assigned to one of the four aspectual classes, using criteria to be discussed in section 2.4. These criteria are intended to detect the view that is mainly associated with each verb in the particular domain that is being examined. Following [Dowty 86], [Moens 87], [Vlach 93], and others, aspectual class is treated as a property of not only verbs, but also verb phrases, clauses, and sentences. Normally, all verb forms will inherit the aspectual classes of the corresponding base forms. Verb phrases, clauses, or sentences will normally inherit the aspectual classes of their main verb forms. Some linguistic mechanisms (e.g. the progressive or some temporal adverbials), however, may cause the aspectual class of a verb form to differ from that of the base form, or the aspectual class of a verb phrase, clause, or sentence to differ from that of its main verb form. The aspectual class of each verb phrase, clause, or sentence is intended to reflect the view that users typically have in mind when using that expression in the particular domain.

In the case of a verb like “*to run*”, that typically involves a culminating activity view when used with an expression that specifies a destination or specific distance (e.g. “*to run to the station/five miles*”), but an activity view when used on its own, it will be assumed that there are two different homonymous verbs “*to run*”. One has a culminating activity base form, and requires a complement that specifies a destination or

specific distance. The other has an activity base form, and requires no such complement. A similar distinction would be introduced in the case of verbs whose aspectual class depends on whether or not the verb’s object denotes a countable or mass entity (e.g. “*to drink a bottle of wine*” vs. “*to drink wine*”; see [Mourelatos 78]).

Similarly, when a verb can be used in a domain with both habitual and non-habitual meanings (e.g. “*BA737 (habitually) departs from Gatwick.*” vs. “*BA737 (actually) departed from Gatwick five minutes ago.*”), a distinction will be made between a homonym with a habitual meaning, and a homonym with a non-habitual meaning.¹ The base forms of habitual homonyms are classified as states. (This agrees with Vendler, Vlach [Vlach 93], and Moens and Steedman [Moens & Steedman 88], who all classify habituais as states.) The aspectual classes of non-habitual homonyms depend on the verb and the application domain. Approaches that do not postulate homonyms are also possible (e.g. claiming that “*to run*” is an activity which is transformed into a culminating activity by “*the station*”). The homonyms method, however, leads to a more straight forward treatment in the HPSG grammar of chapter 4 (where the base form of each homonym is mapped to a different sign).

In the rest of this thesis, I refer to verbs whose base forms are classified as states, activities, culminating activities, or points as *state verbs*, *activity verbs*, *culminating activity verbs*, and *point verbs*.

2.4 Criteria for classifying base verb forms

This section discusses the criteria that determine the aspectual class of a verb’s base form in a particular NLITDB domain. Three criteria are employed, and they are applied in the order of figure 2.1.

2.4.1 The simple present criterion

The first criterion distinguishes state verbs (verbs whose base forms are states) from point, activity, and culminating activity verbs. If the simple present of a verb can be used (in the particular domain) in single-clause questions with non-futurate meanings, the verb is a state one; otherwise it is a point, activity, or culminating activity verb.

¹ When discussing sentences with multiple readings, I often use parenthesised words (e.g. “(*habitually*)”) to indicate which reading is being considered.

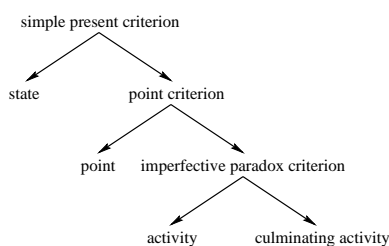


Figure 2.1: Determining the aspectual class of a verb's base form

For example, in domains where (2.1) and (2.2) are possible, “*to contain*” and “*to own*” are state verbs.

(2.1) Does any tank contain oil?

(2.2) Which employees own a car?

Some clarifications are needed. First, the simple present sometimes refers to something that is scheduled to happen. For example, (2.3) could refer to a scheduled assembling (in that case, (2.3) is very similar to (2.4)). I consider this meaning of (2.3) futurate. Hence, this use of (2.3) does not constitute evidence that “*to assemble*” is a state verb.

(2.3) When does J.Adams assemble engine 5?

(2.4) When will J.Adams assemble engine 5?

In reporting contexts, the simple present of verbs whose base forms I would not want to be classified as states can be used with a non-futurate meaning. For example, in a context where the speaker reports events as they happen, (2.5) is possible. (This use of the simple present is unlikely in NLITDB questions.)

(2.5) J.Adams arrives. He moves the container. He fixes the engine.

The simple present criterion examines questions directed to a NLITDB, not sentences from other contexts. Hence, (2.5) does not constitute evidence that “*to arrive*”, “*to move*”, and “*to fix*” are state verbs.

The reader is reminded that when verbs have both habitual and non-habitual meanings, I distinguish between habitual and non-habitual homonyms (section 2.3). Ignoring scheduled-to-happen meanings (that do not count for the simple present criterion), (2.6) and (2.7) can only have habitual meanings.

(2.6) Which flight lands on runway 2?

(2.7) Does any doctor smoke?

(2.6) asks for a flight that habitually lands on runway 2, and (2.7) for doctors that are smokers. That is, (2.6) and (2.7) can only be understood as involving the habitual homonyms of “*to land*” and “*to smoke*”. (In contrast, (2.8) and (2.9) can be understood with non-habitual meanings, i.e. as involving the non-habitual homonyms.)

(2.8) Which flight is landing on runway 2?

(2.9) Is any doctor smoking?

Therefore, in domains where (2.6) and (2.7) are possible, the habitual “*to land*” and “*to smoke*” are state verbs. (2.6) and (2.7) do not constitute evidence that the non-habitual “*to land*” and “*to smoke*” are state verbs.

2.4.2 The point criterion

The second criterion, the *point criterion*, distinguishes point verbs from activity and culminating activity ones (state verbs will have already been separated by the simple present criterion; see figure 2.1). The point criterion is based on the fact that some verbs will be used to describe kinds of world situations that are modelled in the database as being always instantaneous. If a verb describes situations of this kind, its base form should be classified as point; otherwise, it should be classified as activity or culminating activity.

In section 2.4.5, for example, I consider a hypothetical airport database. That database does not distinguish between the times at which a flight starts or stops entering an airspace sector. Entering a sector is modelled as instantaneous. Also, in the airport domain “*to enter*” is only used to refer to flights entering sectors. Consequently, in that domain “*to enter*” is a point verb. If “*to enter*” were also used to refer to, for example, groups of passengers entering planes, and if situations of this kind were modelled in the database as non-instantaneous, one would have to distinguish between two homonyms “*to enter*”, one used with flights entering sectors, and one with passengers entering planes. The first would be a point verb; the second would not.

The person applying the criterion will often have to decide exactly what is or is not part of the situations described by the verbs. The database may store, for example,

the time-points at which a flight starts to board, finishes boarding, starts to taxi to a runway, arrives at the runway, and leaves the ground. Before classifying the non-habitual “*to depart*”, one has to decide exactly what is or is not part of departing. Is boarding part of departing, i.e. is a flight departing when it is boarding? Is taxiing to a runway part of departing? Or does departing include only the time at which the flight actually leaves the ground? If a flight starts to depart when it starts to board, and finishes departing when it leaves the ground, then the base form of “*to depart*” should not be classified as point, because the database does not treat departures as instantaneous (it distinguishes between the beginning of the boarding and the time when the flight leaves the ground). If, however, departing starts when the front wheels of the aircraft leave the ground and finishes when the rear wheels leave the ground, the base form of “*to depart*” *should* be classified as point, because the database does not distinguish the two times. In any case, the user should be aware of what “*to depart*” is taken to mean.

The point criterion is similar to claims in [Vendler 67], [Singh & Singh 92], [Vlach 93], and elsewhere that achievement (point) verbs denote instantaneous situations.

2.4.3 The imperfective paradox criterion

The third criterion distinguishes activity from culminating activity verbs (state and point verbs will have already been separated by the point and simple present criteria). The criterion is based on the imperfective paradox (section 1.2.2). Assertions containing the past continuous and simple past of the verbs, like (2.10) – (2.13), are considered.

(2.10) John was running.

(2.11) John ran.

(2.12) John was building a house.

(2.13) John built a house.

The reader is reminded that assertions are treated as yes/no questions (section 1.4). If an affirmative answer to the past continuous assertion implies an affirmative answer to the simple past assertion (as in (2.10) – (2.11)), the verb is an activity one; otherwise (e.g. (2.12) – (2.13)), it is a culminating activity one.

As will be discussed in section 2.5.3, the past continuous sometimes has a futurate meaning. Under this reading, (2.10) means “*John was going to run.*”, and an affirmative answer to (2.10) does not necessarily imply an affirmative answer to (2.11). When applying the imperfective paradox criterion, the past continuous must not have its futurate meaning. In various forms, the imperfective paradox criterion has been used in [Vendler 67], [Vlach 93], [Kent 93], and elsewhere.

2.4.4 Other criteria

The three criteria above are not the only ones that could be used. The behaviour of verbs when appearing in various forms or when combining with some temporal adverbials varies depending on their aspectual classes. Alternative criteria can be formulated by observing this behaviour. For example, some authors classify verbs (or situations denoted by verbs) by observing how easily they appear in progressive forms (to be discussed in section 2.5.3), how easily they combine with “*for ...*” and “*in ...*” duration adverbials (sections 2.9.3 and 2.9.4 below), or what the verbs entail about the start or the end of the described situation when they combine with “*at ...*” temporal adverbials (section 2.9.1 below). In some cases, the person classifying the base verb forms may be confronted with a verb for which the three criteria of sections 2.4.1 – 2.4.3 do not yield a clear verdict. In such cases, additional evidence for or against classifying a base verb form into a particular class can be found by referring to following sections, where the typical behaviour of each class is examined.

2.4.5 Classifying base verb forms in the airport domain

To illustrate the use of the criteria of sections 2.4.1 – 2.4.3, I now consider a hypothetical NLITDB to a temporal database that contains information about the air-traffic of an airport. (I borrow some terminology from [Sripada *et al.* 94]. The airport domain will be used in examples throughout this thesis.) The airport database shows the times when flights arrived at, or departed from, the airport, the times flights spent circling around the airport while waiting for permission to land, the runways they landed on or took off from, the gates where the flights boarded, etc. The database is occasionally queried using the NLITDB to determine the causes of accidents, and to collect data that are used to optimise the airport’s traffic-handling strategies.

The airport's airspace is divided into sectors. Flights approaching or leaving the airport cross the boundaries of sectors, each time *leaving* a sector and *entering* another one. The airport is very busy, and some of its runways may also *be closed* for maintenance. Hence, approaching flights are often instructed to *circle* around the airport until a runway *becomes* free. When a runway is freed, flights *start to land*. Landing involves following a specific procedure. In some cases, the pilot may abort the landing procedure before completing it. Otherwise, the flight lands on a runway, and it then *taxies* to a gate that *is free*. The moment at which the flight *reaches* the gate is considered the time at which the flight *arrived* (reaching a location and arriving are modelled as instantaneous). Normally (habitually) each flight arrives at the same gate and time every day. Due to traffic congestion, however, a flight may sometimes arrive at a gate or time other than its normal ones.

Before *taking off*, each flight is *served* by a service company. This involves carrying out a specific set of tasks. Unless all tasks have been carried out, the service is incomplete. Each service company normally (habitually) services particular flights. Sometimes, however, a company may be asked to service a flight that it does not normally service. After being serviced, a flight may be *inspected*. Apart from flights, inspectors also inspect gates and runways. In all cases, there are particular tasks to be carried out for the inspections to be considered complete.

Shortly before taking off, flights start to *board*. Unless all the passengers that have checked in enter the aircraft, the boarding is not complete, and the flight cannot depart. (There are special arrangements for cases where passengers are too late.) The flight then *leaves* the gate, and that moment is considered the time at which the flight *departed* (leaving a location and departing are modelled as instantaneous). Normally (habitually) each flight departs from the same gate at the same time every day. Sometimes, however, flights depart from gates, or at times, other than their normal ones. After leaving its gate, a flight may be told to *queue* for a particular runway, until that runway becomes free. When the runway is free, the flight starts to *take off*, which involves following a specific procedure. As with landings, the pilot may abort the taking off procedure before completing it.

The database also records the states of parts of the airport's emergency system. There are, for example, emergency tanks, used by the fire-brigade. Some of those may *contain* water, others may contain foam, and others may *be empty* for maintenance.

state verbs	activity verbs	culm. activity verbs	point verbs
service (habitually) arrive (habitually) depart (habitually) contain be (non-auxiliary)	circle taxi (no destination) queue	land take off service (actually) inspect board taxi (to destination)	cross enter become start/begin stop/finish reach leave arrive (actually) depart (actually)

Table 2.1: Verbs of the airport domain

Table 2.1 shows some of the verbs that are used in the airport domain. “*To depart*”, “*to arrive*”, and “*to service*” are used with both habitual and non-habitual meanings. (2.14) and (2.16), for example, can have habitual meanings. In (2.15) and (2.17), the verbs are probably used with their non-habitual meanings. I distinguish between habitual and non-habitual homonyms of “*to depart*”, “*to arrive*”, and “*to service*” (section 2.3).

(2.14) Which flights depart/arrive at 8:00am?

(2.15) Which flight departed/arrived at 8:00am yesterday?

(2.16) Which company services BA737?

(2.17) Which company serviced BA737 yesterday?

I also distinguish between two homonyms of “*to taxi*”, one that requires a destination-denoting complement (as in “*BA737 was taxiing to gate 2.*”), and one that requires no such complement (as in “*BA737 was taxiing.*”).

The simple present criterion and sentences like (2.18), (2.19), (2.14), and (2.16) imply that the non-auxiliary “*to be*”, “*to contain*”, and the habitual “*to depart*”, “*to arrive*”, and “*to service*” are state verbs.

(2.18) Which gates are free?

(2.19) Does any tank contain foam?

All other verbs of table 2.1 are not state verbs. For example, (excluding habitual and futurate meanings) (2.20) – (2.22) sound unlikely or odd in the airport domain. (2.23) – (2.25) would be used instead.

- (2.20) ?Which flights circle?
- (2.21) ?Which flight taxies to gate 2?
- (2.22) ?Which flight departs?
- (2.23) Which flights are circling?
- (2.24) Which flight is taxiing to gate 2?
- (2.25) Which flight is departing?

The verbs in the rightmost column of table 2.1 are used in the airport domain to refer to situations which I assume are modelled as instantaneous in the database. Consequently, by the point criterion these are all point verbs. In contrast, I assume that the situations of the verbs in the two middle columns are not modelled as instantaneous. Therefore, those are activity or culminating activity verbs.

In the airport domain, a sentence like (2.27) means that BA737 spent some time circling around the airport. It does not imply that BA737 completed any circle around the airport. Hence, an affirmative answer to (2.26) implies an affirmative answer to (2.27). By the imperfective paradox criterion, “*to circle*” is an activity verb.

- (2.26) BA737 was circling.
- (2.27) BA737 circled.

Similar assertions and the imperfective paradox criterion imply that “*to taxi*” (no destination) and “*to queue*” are also activity verbs. In contrast, the verbs in the third column of table 2.1 are culminating activity verbs. For example, in the airport domain an affirmative answer to (2.28) does not imply an affirmative answer to (2.29): J.Adams may have aborted the inspection before completing all the inspection tasks, in which case the inspection is incomplete.

- (2.28) J.Adams was inspecting runway 5.
- (2.29) J.Adams inspected runway 5.

2.5 Verb tenses

I now turn to verb tenses. I use “tense” with the meaning it has in traditional English grammar textbooks (e.g. [Thomson & Martinet 86]). For example, “*John sings.*” and

“*John is singing.*” will be said to be in the simple present and present continuous tenses respectively. In linguistics, “tense” is not always used in this way. According to [Comrie 85], for example, “*John sings.*” and “*John is singing.*” are in the same tense, but differ aspectually.

Future questions are not examined in this thesis (section 1.4). Hence, future tenses and futurate meanings of other tenses (e.g. the scheduled-to-happen meaning of the simple present; section 2.4.1) will be ignored. To simplify further the linguistic data, the present perfect continuous and past perfect continuous (e.g. “*has/had been inspecting*”) were also not considered: these tenses combine problems from both continuous and perfect tenses. This leaves six tenses to be discussed: simple present, simple past, present continuous, past continuous, present perfect, and past perfect.

2.5.1 Simple present

The framework of this thesis allows the simple present to be used only with state verbs, to refer to a situation that holds at the present (e.g. (2.30), (2.31)).

(2.30) Which runways are closed?

(2.31) Does any tank contain water?

Excluding the scheduled-to-happen meaning (which is ignored in this thesis), (2.32) can only be understood as asking for the current normal (habitual) servicer of BA737. Similarly, (2.33) can only be asking for the current normal departure gate of BA737. (2.32) would not be used to refer to a company that is actually servicing BA737 at the present moment (similar comments apply to (2.33)). That is, (2.32) and (2.33) can only involve the habitual homonyms of “*to service*” and “*to depart*” (which are state verbs), not the non-habitual ones (which are culminating activity and point verbs respectively; see table 2.1). This is consistent with the assumption that the simple present can only be used with state verbs.

(2.32) Which company services BA737?

(2.33) Which flights depart from gate 2?

In the airport domain, “*to circle*” is an activity verb (there is no state habitual homonym). Hence, (2.34) is rejected. This is as it should be, because (2.34) can

only be understood with a habitual meaning, a meaning which is not available in the airport domain (there are no circling habits).

(2.34) Does BA737 circle?

The simple present can also be used with non-state verbs to describe events as they happen (section 2.4.1), or with a historic meaning (e.g. “*In 1673 a fire destroys the palace.*”), but these uses are extremely unlikely in NLITDB questions.

2.5.2 Simple past

Like the simple present, the simple past can be used with verbs from all four classes (e.g. (2.35) – (2.40)).

(2.35) Which tanks contained water on 1/1/95?

(2.36) Did BA737 circle on 1/1/95?

(2.37) Which flights (actually) departed from gate 2 on 1/1/95?

(2.38) Which flights (habitually) departed from gate 2 in 1994?

(2.39) Which company (actually) serviced BA737 yesterday?

(2.40) Which company (habitually) serviced BA737 last year?

(2.37) – (2.40) show that both the habitual and the non-habitual homonyms of verbs like “*to depart*” or “*to service*” are generally possible in the simple past. (2.41) is ambiguous. It may refer either to flights that actually departed (perhaps only once) from gate 2 in 1994, or to flights that normally (habitually) departed from gate 2 in 1994.

(2.41) Which flights departed from gate 2 in 1994?

The simple past of culminating activity verbs normally implies that the situation of the verb reached its climax. For example, in (2.42) the service must have been completed, and in (2.43) BA737 must have reached gate 2 for the answer to be affirmative.

(2.42) Did Airserve service BA737?

(2.43) Did BA737 taxi to gate 2?

(2.44) BA737 was taxiing to gate 2 but never reached it.

Some native English speakers consider simple negative answers to (2.42) and (2.43) unsatisfactory, if for example BA737 was taxiing to gate 2 but never reached it. Although they agree that strictly speaking the answer should be negative, they consider (2.44) a much more appropriate answer. To generate answers like (2.44), a mechanism for *cooperative responses* is needed, an issue not addressed in this thesis (section 1.4).

The simple past (and other tenses) often has an *anaphoric* nature. For example, (2.42) probably does not ask if Airserve serviced BA737 at *any* time in the past. (2.42) would typically be used with a particular time in mind (e.g. the present day), to ask if Airserve serviced BA737 during that time. As will be discussed in section 2.12, a temporal anaphora resolution mechanism is needed to determine the time the speaker has in mind. The framework of this thesis currently provides no such mechanism, and (2.42) is taken to refer to any past time. (The same approach is adopted with all other tenses that refer to past situations.)

2.5.3 Present continuous and past continuous

Futurate meanings: The present and past continuous can be used with futurate meanings. In that case, (2.45) is similar to (2.46).

(2.45) Who is/was inspecting BA737?

(2.46) Who will/would inspect BA737?

Futurate meanings of tenses are not examined in this thesis. Hence, this use of the present and past continuous will be ignored.

Activity and culminating activity verbs: The present and past continuous can be used with activity and culminating activity verbs to refer to a situation that is or was in progress (e.g. (2.47) – (2.48) from the airport domain).

(2.47) Are/Were any flights circling?

(2.48) Is/Was BA737 taxiing to gate 2?

In the case of culminating activity verbs, there is no requirement for the climax to be reached at any time. The past continuous version of (2.48), for example, does not require BA737 to have reached gate 2 (cf. (2.43)).

Point verbs: The present and past continuous of point verbs often refers to a preparatory process that is or was ongoing, and that normally leads to the instantaneous situation of the verb. For example, in the airport domain where “*to depart*” is a point verb and departing includes only the moment where the flight leaves its gate, one could utter (2.49) when the checking-in is ongoing or when the flight is boarding.

(2.49) BA737 is departing.

The framework of this thesis provides no mechanism for determining exactly which preparatory process is asserted to be in progress. (Should the checking-in be in progress for the response to (2.49) to be affirmative? Should the boarding be ongoing?) Hence, this use of the present and past continuous of point verbs is not allowed. The response to (2.49) will be affirmative only at the time-point where BA737 is leaving its gate (as will be discussed in section 5.2.2, the database may model time-points as corresponding to minutes or even whole days). To avoid misunderstandings, the NLITDB should warn the user that (2.49) is taken to refer to the actual (instantaneous) departure, not to any preparatory process. This is again a case for cooperative responses, an issue not examined in this thesis.

State verbs: It has often been observed (e.g. Vendler’s tests in section 2.2) that state verbs are not normally used in progressive forms. For example, (2.50) and (2.52) are easily rejected by most native speakers. (I assume that “*to own*” and “*to consist*” would be classified as state verbs, on the basis that simple present questions like (2.51) and (2.53) are possible.)

(2.50) *Who is owning five cars?

(2.51) Who owns five cars?

(2.52) *Which engine is consisting of 34 parts?

(2.53) Which engine consists of 34 parts?

The claim that state verbs do not appear in the progressive is challenged by sentences like (2.54) (from [Smith 86], cited in [Passegnau 88]; [Kent 93] and [Vlach 93] provide similar examples). (2.54) shows that the non-auxiliary “*to be*”, which is typically classified as state verb, can be used in the progressive.

(2.54) My daughter is being very naughty.

Also, some native English speakers find (2.55) and (2.56) acceptable (though they would use the non-progressive forms instead). (I assume that “*to border*” would be classified as state verb, on the basis that “*Which countries border France?*” is possible.)

(2.55) ?Tank 4 was containing water when the bomb exploded.

(2.56) ?Which countries were bordering France in 1937?

Not allowing progressive forms of state verbs also seems problematic in questions like (2.57). (2.57) has a reading which is very similar to the habitual reading of (2.58) (habitually serviced BA737 in 1994).

(2.57) Which company was servicing BA737 in 1994?

(2.58) Which company serviced (habitually) BA737 in 1994?

The reader is reminded that in the airport domain I distinguish between a habitual and a non-habitual homonym of “*to service*”. The habitual homonym is a state verb, while the non-habitual one is a culminating activity verb. If progressive forms of state verbs are not allowed, then only the non-habitual homonym (actually servicing) is possible in (2.57). This does not account for the apparently habitual meaning of (2.57).

One could argue that the reading of (2.57) is not really habitual but *iterative* (servicing many times, as opposed to having a servicing habit). As pointed out in [Comrie 76] (p. 27), the mere repetition of a situation does not suffice for the situation to be considered a habit. (2.59), for example, can be used when John is banging his hand on the table repeatedly. In this case, it seems odd to claim that (2.59) asserts that John has the habit of banging his hand on the table, i.e. (2.59) does not seem to be equivalent to the habitual (2.60).

(2.59) John is banging his hand on the table.

(2.60) John (habitually) bangs his hand on the table.

In sentences like (2.57) – (2.58), however, the difference between habitual and iterative meaning is hard to define. For simplicity, I do not distinguish between habitual and iterative readings, and I allow state verbs to be used in progressive forms (with the same meanings as the non-progressive forms). This causes (2.57) to receive two readings: one involving the habitual “*to service*” (servicing habitually in 1994), and one involving

the non-habitual “*to service*” (actually servicing at some time in 1994; this reading is more likely without the “*in 1994*”). (2.50) and (2.52) are treated as equivalent to (2.51) and (2.53).

As will be discussed in section 2.9, I assume that progressive tenses cause an aspectual shift from activities and culminating activities to states. In the airport domain, for example, although the base form of “*to inspect*” is a culminating activity, “*was inspecting*” is a state.

2.5.4 Present perfect

Like the simple past, the present perfect can be used with verbs of all four classes to refer to past situations (e.g. (2.61) – (2.65)). With culminating activity verbs, the situation must have reached its climax (e.g. in (2.65) the service must have been completed).

(2.61) Has BA737 (ever) been at gate 2?

(2.62) Which flights have circled today?

(2.63) Has BA737 reached gate 2?

(2.64) Which company has (habitually) serviced BA737 this year?

(2.65) Has Airserve (actually) serviced BA737?

It has often been claimed (e.g. [Moens 87], [Vlach 93], [Blackburn *et al.* 94]) that the English present perfect asserts that some consequence of the past situation holds at the present. For example, (2.66) seems to imply that there is a consequence of the fact that engine 5 caught fire that still holds (e.g. engine 5 is still on fire, or it was damaged by the fire and has not been repaired). In contrast, (2.67) does not seem to imply (at least not as strongly) that some consequence still holds.

(2.66) Engine 5 has caught fire.

(2.67) Engine 5 caught fire.

Although these claims are intuitively appealing, it is difficult to see how they could be used in a NLITDB. Perhaps in (2.68) the NLITDB should check not only that the landing was completed, but also that some consequence of the landing still holds.

(2.68) Has BA737 landed?

It is unclear, however, what this consequence should be. Should the NLITDB check that the plane is still at the airport? And should the answer be negative if the plane has departed since the landing? Should the NLITDB check that the passengers of BA737 are still at the airport? And should the answer be negative if the passengers have left the airport? Given this uncertainty, the framework of this thesis does not require the past situation to have present consequences.

When the present perfect combines with “*for . . .*” duration adverbials (to be discussed in section 2.9.3), there is often an implication that the past situation still holds at the present (this seems related to claims that the past situation must have present consequences). For example, there is a reading of (2.69) where J.Adams is still a manager. ((2.69) can also mean that J.Adams was simply a manager for two years, without the two years ending at the present moment.) In contrast, (2.70) carries no implication that J.Adams is still a manager (in fact, it seems to imply that he is no longer a manager).

(2.69) J.Adams has been a manager for two years.

(2.70) J.Adams was a manager for two years.

Representing in TOP the still-holding reading of sentences like (2.69) has proven difficult. Hence, I ignore the possible implication that the past situation still holds, and I treat (2.69) as equivalent to (2.70).

The present perfect does not combine felicitously with some temporal adverbials. For example, (2.71) and (2.74) sound at least odd to most native English speakers (they would use (2.72) and (2.75) instead). In contrast, (2.73) and (2.76) are acceptable.

(2.71) ?Which flights have landed yesterday?

(2.72) Which flights landed yesterday?

(2.73) Which flights have landed today?

(2.74) ?Which flights has J.Adams inspected last week?

(2.75) Which flights did J.Adams inspect last week?

(2.76) Which flights has J.Adams inspected this week?

(2.71) – (2.76) suggest that the present perfect can only be used if the time of the adverbial contains not only the time where the past situation occurred, but also the speech time, the time when the sentence was uttered. (A similar explanation is given on p. 167 of [Thomson & Martinet 86].) (2.73) is felicitous, because “*today*” contains the speech time. In contrast, (2.71) is unacceptable, because “*yesterday*” cannot contain the speech time. The hypothesis, however, that the time of the adverbial must include the speech time does not account for the fact that (2.77) is acceptable by most native English speakers (especially if the “*ever*” is added), even if the question is not uttered on a Sunday.

(2.77) Has J.Adams (ever) inspected BA737 on a Sunday?

As pointed out in [Moens & Steedman 88], a superstitious person could also utter (2.78) on a day other than Friday the 13th.

(2.78) They have married on Friday 13th!

One could attempt to formulate more elaborate restrictions, to predict exactly when temporal adverbials can be used with the present perfect. In the case of a NLITDB, however, it is difficult to see why this would be worth the effort, as opposed to simply accepting questions like (2.71) as equivalent to (2.72). I adopt the latter approach.

Given that the framework of this thesis does not associate present consequences with the present perfect, that the still-holding reading of sentences like (2.69) is not supported, and that questions like (2.71) are allowed, there is not much left to distinguish the present perfect from the simple past. Hence, I treat the present perfect as equivalent to the simple past.

2.5.5 Past perfect

The past perfect is often used to refer to a situation that occurred at some past time before some other past time. Following Reichenbach [Reichenbach 47] and many others, let us call the latter time the *reference time*. (2.79) and (2.80) have readings where “*at 5:00pm*” specifies the reference time. In that case, (2.79) asks for flights that Airserve serviced before 5:00pm, and (2.80) asks if BA737 was at gate 2 some time before 5:00pm. (When expressing these meanings, “*by 5:00pm*” is probably preferable.

I claim, however, that “at 5:00pm” can also be used in this way. “By . . . ” adverbials are not examined in this thesis.)

(2.79) Which flights had Airserve serviced at 5:00pm?

(2.80) Had BA737 been at gate 2 at 5:00pm?

With culminating activity verbs, the climax must have been reached before (or possibly at) the reference time. For example, in (2.79) the services must have been completed up to 5:00pm. Perhaps some consequence of the past situation must still hold at the reference time (see similar comments about the present perfect in section 2.5.4). As with the present perfect, however, I ignore such consequential links.

When the past perfect combines with temporal adverbials, it is often unclear if the adverbial is intended to specify the reference time or directly the time of the past situation. For example, (2.81) could mean that BA737 had already reached gate 2 at 5:00pm, or that it reached it at 5:00pm. In the latter case, (2.81) is similar to the simple past (2.82), except that (2.81) creates the impression of a longer distance between the time of the reaching and the speech time.

(2.81) BA737 had reached gate 2 at 5:00pm.

(2.82) BA737 reached gate 2 at 5:00pm.

When the past perfect combines with “for . . . ” duration adverbials and a reference time is specified, there is often an implication that the past situation still held at the reference time. (A similar implication arises in the case of the present perfect; see section 2.5.4.) For example, (2.83) seems to imply that J.Adams was still a manager on 1/1/94. As in the case of the present perfect, I ignore this implication, for reasons related to the difficulty of representing it in TOP.

(2.83) J.Adams had been a manager for two years on 1/1/94.

As will be discussed in section 2.9, I assume that the past perfect triggers an aspectual shift to state (e.g. the base form of “to inspect” is a culminating activity, but “had inspected” is a state). This shift seems to be a property of all perfect tenses. For reasons, however, related to the fact that I treat the present perfect as equivalent to the simple past (section 2.5.4), I do not postulate any shift in the case of the present perfect.

2.6 Special temporal verbs

Through their tenses, all verbs can convey temporal information. Some verbs, however, like “*to begin*” or “*to precede*”, are of a more inherently temporal nature. These verbs differ from ordinary ones (e.g. “*to build*”, “*to contain*”) in that they do not describe directly situations, but rather refer to situations introduced by other verbs or nouns. (A similar observation is made in [Passonneau 88].) In (2.84), for example, “*to begin*” refers to the situation of “*to build*”. “*To start*”, “*to end*”, “*to finish*”, “*to follow*”, “*to continue*”, and “*to happen*” all belong to this category of special temporal verbs.

(2.84) They began to build terminal 9 in 1985.

From all the special temporal verbs, I have considered only “*to start*”, “*to begin*”, “*to stop*”, and “*to finish*”. I allow “*to start*”, “*to begin*”, “*to end*”, and “*to finish*” to be used with state and activity verbs, even though with state verbs “*to begin*” and “*to finish*” usually sound unnatural (e.g. (2.85)), and with activity verbs (e.g. (2.86)) it could be argued that the use of “*to begin*” or “*to finish*” signals that the speaker has in mind a culminating activity (not activity) view of the situation.

(2.85) ?Which tank began to contain/finished containing water on 27/7/95?

(2.86) Which flight began/finished circling at 5:00pm?

When combining with culminating activity verbs, “*to start*” and “*to begin*” have the same meanings. “*To stop*” and “*to finish*”, however, differ: “*to finish*” requires the climax to be reached, while “*to stop*” requires the action or change to simply stop (possibly without being completed). For example, in (2.87) the service must have simply stopped, while in (2.88) it must have been completed.

(2.87) Which company stopped servicing (actually) BA737 at 5:00pm?

(2.88) Which company finished servicing (actually) BA737 at 5:00pm?

With point verbs (like “*to enter*” and “*to leave*” in the airport domain), the use of “*to start*”, “*to begin*”, “*to stop*”, and “*to finish*” (e.g. (2.89), (2.90)) typically signals that the person submitting the question is unaware that the situation of the point verb is taken to be instantaneous. In these cases, I ignore the temporal verbs (e.g. (2.89) is treated as (2.91)). Ideally, the NLITDB would also warn the user that the temporal

verb is ignored, and that the situation is modelled as instantaneous (another case for cooperative responses; see section 1.4). The framework of this thesis, however, provides no mechanism for generating such warnings.

(2.89) Which flight started to enter sector 2 at 5:00pm?

(2.90) Which flight finished leaving gate 2 at 5:00pm?

(2.91) Which flight entered sector 2 at 5:00pm?

2.7 Temporal nouns

Some nouns have a special temporal nature. Nouns like “*development*” or “*inspection*”, for example, are similar to verbs, in that they introduce world situations that occur in time. The role of “*development*” in (2.92) is very similar to that of “*to develop*” in (2.93).

(2.92) When did the development of MASQUE start?

(2.93) When did they start to develop MASQUE?

Other nouns indicate temporal order (e.g. “*predecessor*”, “*successor*”), or refer to start or end-points (e.g. “*beginning*”, “*end*”). Finally, many nouns (and proper names) refer to time periods, points, or generally entities of the temporal ontology (e.g. “*minute*”, “*July*”, “*event*”).

From all the temporal nouns (and proper names), this thesis examines only nouns like “*year*”, “*month*”, “*week*”, “*day*”, “*minute*”, “*second*”, “*1993*”, “*July*”, “*1/1/85*”, “*Monday*”, “*3:05pm*”. Temporal nouns of a more abstract nature (e.g. “*period*”, “*point*”, “*interval*”, “*event*”, “*time*”, “*duration*”), nouns referring to start or end-points, nouns introducing situations, and nouns of temporal precedence are not considered.

2.8 Temporal adjectives

There are also adjectives of a special temporal nature. Some refer to a temporal order (e.g. “*current*”, “*previous*”, “*earliest*”), others refer to durations (e.g. “*brief*”, “*longer*”), and others specify frequencies (e.g. “*annual*”, “*daily*”). Adjectives of this

kind are not examined in this thesis, with the exception of “*current*” which is supported to illustrate some points related to temporal anaphora (these points will be discussed in section 2.11). (“Normal” adjectives, like “*open*” and “*free*”, are also supported.)

2.9 Temporal adverbials

This section discusses adverbials that convey temporal information.

2.9.1 Punctual adverbials

Some adverbials are understood as specifying time-points. Following [Vlach 93], I call these *punctual adverbials*. In English, punctual adverbials are usually prepositional phrases introduced by “*at*” (e.g. “*at 5:00pm*”, “*at the end of the inspection*”). In this thesis, only punctual adverbials consisting of “*at*” and clock-time expressions (e.g. “*at 5:00pm*”) are considered.

With states: When combining with state expressions, punctual adverbials specify a time where the situation of the state expression holds. There is usually no implication that the situation of the state starts or stops at the time of the adverbial. (2.94), for example, asks if tank 5 was empty at 5:00pm. There is no requirement that the tank must have started or stopped being empty at 5:00pm. Similar comments apply to (2.95).

(2.94) Was tank 5 empty at 5:00pm?

(2.95) Which flight was at gate 2 at 5:00pm?

In other words, with states punctual adverbials normally have an *interjacent* meaning, not an *inchoative* or *terminal* one. (“Interjacent”, “inchoative”, and “terminal” are borrowed from [Kent 93]. Kent explores the behaviour of “*at*”, “*for*”, and “*in*” adverbials, and arrives at conclusions similar to the ones presented here.)

In narrative contexts, punctual adverbials combining with states sometimes have inchoative meanings. For example, the “*at 8:10am*” in (2.96) most probably specifies the time when J.Adams arrived (started being) in Glasgow. In NLITDB questions, however, this inchoative meaning seems unlikely. For example, it seems unlikely that (2.97)

would be used to enquire about persons that *arrived* in Glasgow at 8:10am. Hence, for the purposes of this thesis, it seems reasonable to assume that punctual adverbials combining with states always have interjacent meanings.

(2.96) J.Adams left Edinburgh early in the morning, and at 8:10am he was in Glasgow.

(2.97) Who was in Glasgow at 8:10am?

With points: With point expressions, punctual adverbials specify the time where the instantaneous situation of the point expression takes place (e.g. (2.98), (2.99); “*to enter*” and “*to reach*” are point verbs in the airport domain).

(2.98) Which flight entered sector 2 at 23:02?

(2.99) Which flight reached gate 5 at 23:02?

(2.100) is ambiguous. It may either involve the non-habitual homonym of “*to depart*” (this homonym is a point verb in the airport domain), in which case 5:00pm is the time of the actual departure, or the state habitual homonym (to depart habitually at some time), in which case 5:00pm is the habitual departure time. In the latter case, I treat “*at 5:00pm*” as a prepositional phrase complement of the habitual “*to depart*”, not as a temporal adverbial. This reflects the fact that the “*at 5:00pm*” does not specify a time when the habit holds, but it forms part of the description of the habit, i.e. it is used in a way very similar to how “*from gate 2*” is used in (2.101).

(2.100) Which flight departed at 5:00pm?

(2.101) Which flight departed (habitually) from gate 2 (last year)?

With activities: With activities, punctual adverbials usually have an inchoative meaning, but an interjacent one is also possible in some cases. (2.102), for example, could refer to a flight that either joined the queue of runway 2 at 5:00pm or was simply in the queue at 5:00pm. (In the airport domain, “*to queue*” and “*to taxi*” (no destination) are activity verbs.) The inchoative meaning seems the preferred one in (2.102). It also seems the preferred one in (2.103), though an interjacent meaning is (arguably) also possible. The interjacent meaning is easier to accept in (2.104).

(2.102) Which flight queued for runway 2 at 5:00pm?

(2.103) BA737 taxied at 5:00pm.

(2.104) Which flights circled at 5:00pm?

With past continuous forms of activity verbs, however, punctual adverbials normally have only interjacent meanings (compare (2.102) and (2.103) to (2.105) and (2.106)). (One would not normally use punctual adverbials with present continuous forms, since in that case the situation is known to take place at the present.)

(2.105) Which flight was queueing for runway 2 at 5:00pm?

(2.106) BA737 was taxiing at 5:00pm.

To account for sentences like (2.105) and (2.106) (and other phenomena to be discussed in following sections), I classify the progressive tenses (present and past continuous) of activity and culminating activity verbs as states. For example, in the airport domain, the base form of “*to queue*” is an activity. Normally, all other forms of the verb (e.g. the simple past) inherit the aspectual class of the base form. The progressive tenses (e.g. “*is queueing*”, “*was queueing*”) of the verb, however, are states. (The progressive can be seen as forcing an aspectual shift from activities or culminating activities to states. No such aspectual shift is needed in the case of point verbs.) This arrangement, along with the assumption that punctual adverbials combining with states have only interjacent meanings, accounts for the fact that (2.105) and (2.106) have only interjacent meanings. In various forms, assumptions that progressive tenses cause aspectual shifts to states have also been used in [Dowty 86], [Moens 87], [Vlach 93], [Kent 93], and elsewhere.

With culminating activities: When combining with culminating activities, punctual adverbials usually have inchoative or terminal meanings (when they have terminal meanings, they specify the time when the climax was reached). The terminal reading is the preferred one in (2.107). In (2.108) both readings seem possible. In (2.109) the inchoative meaning seems the preferred one. (In the airport domain, “*to land*”, “*to taxi*” (to destination), and “*to inspect*” are culminating activity verbs.)

(2.107) Which flight landed at 5:00pm?

(2.108) Which flight taxied to gate 4 at 5:00pm?

(2.109) Who inspected BA737 at 5:00pm?

Perhaps, as with activities, an interjacent meaning is sometimes also possible (e.g. (2.108) would refer to a flight that was on its way to gate 4 at 5:00pm). This may be true, but with culminating activities the inchoative or terminal reading is usually much more dominant. For simplicity, I ignore the possible interjacent meaning in the case of culminating activities.

With past continuous forms of culminating activity verbs, punctual adverbials normally have only interjacent meanings. Compare, for example, (2.107) – (2.109) to (2.110) – (2.112). This is in accordance with the assumption that the progressive tenses of activity and culminating activity verbs are states.

(2.110) Which flight was landing at 5:00pm?

(2.111) Which flight was taxiing to gate 4 at 5:00pm?

(2.112) Who was inspecting BA737 at 5:00pm?

With past perfect: As discussed in section 2.5.5, in sentences like (2.113) the adverbial can be taken to refer either directly to the taxiing (the taxiing started or ended at 5:00pm) or to the reference time (the taxiing had already finished at 5:00pm).

(2.113) BA737 had taxied to gate 2 at 5:00pm.

(2.114) BA737 had [taxied to gate 2 at 5:00pm].

(2.115) BA737 [had taxied to gate 2] at 5:00pm.

The way in which sentences like (2.113) are treated in this thesis will become clearer in chapter 3. A rough description, however, can be given here. (2.113) is treated as syntactically ambiguous between (2.114) (where the adverbial applies to the past participle “taxied”) and (2.115) (where the adverbial applies to the past perfect “had taxied”). The past participle (“taxied”) inherits the aspectual class of the base form, and refers directly to the situation of the verb (the taxiing). In contrast, the past perfect (“had taxied”) is always classified as state (the past perfect can be seen as causing an aspectual shift to state), and refers to a time-period that starts immediately after the end of the situation of the past participle (the end of the taxiing), and extends up to the end of time. Let us call this period the *consequent period*.

In the airport domain, the base form of “to taxi” (to destination) is a culminating activity. Hence, the past participle “taxied” (which refers directly to the taxiing)

is also a culminating activity. In (2.114), a punctual adverbial combines with the (culminating activity) past participle. According to the discussion above, two readings arise: an inchoative (the taxiing started at 5:00pm) and a terminal one (the taxiing finished at 5:00pm). In contrast, in (2.115) the punctual adverbial combines with the past perfect “*had taxied*”, which is a state expression that refers to the consequent period. Hence, only an interjacent reading arises: the time of the adverbial must simply be within the consequent period (there is no need for the adverbial’s time to be the beginning or end of the consequent period). This requires the taxiing to have been completed at the time of the adverbial. A similar arrangement is used when the past perfect combines with period adverbials, duration “*for ...*” and “*in ...*” adverbials, or temporal subordinate clauses (to be discussed in following sections). The assumption that the past perfect causes an aspectual shift to state is similar to claims in [Moens 87], [Vlach 93], and elsewhere, that English perfect forms are (or refer to) states.

Lexical, consequent, and progressive states: There is sometimes a need to distinguish between expressions that are states because they have inherited the state aspectual class of a base verb form, and expressions that are states because of an aspectual shift introduced by a past perfect or a progressive tense. Following [Moens 87], I use the terms *lexical state*, *consequent state*, and *progressive state* to distinguish the three genres. In the airport domain, for example, the base form of “*to queue*” is a lexical state. The simple past “*queued*” and the past participle “*queued*” are also lexical states. The past perfect “*had queued*” is a consequent state, while the present continuous form “*is queueing*” is a progressive state.

Finally, for reasons that will be discussed in section 4.16, I assume that punctual adverbials cause the aspectual class of the syntactic constituent they modify to become point. In (2.115), for example, the “*taxied to gate 2*” inherits the culminating activity aspectual class of the base form. The past perfect causes the aspectual class of “*had taxied to gate 2*” to become consequent state. Finally, the “*at 5:00pm*” causes the aspectual class of “*had departed at 5:00pm*” to become point. Table 2.2 summarises the main points of this section.

meanings of punctual adverbials	
with state	interjacent
with activity	inchoative or interjacent
with culm. activity	inchoative or terminal
with point	specifies time of instantaneous situation
The resulting aspectual class is point.	

Table 2.2: Punctual adverbials in the framework of this thesis

2.9.2 Period adverbials

Unlike punctual adverbials, which are understood as specifying points in time, adverbials like “*in 1991*”, “*on Monday*”, “*yesterday*” (e.g. (2.116) – (2.118)) are usually understood as specifying longer, non-instantaneous periods of time. In (2.116), for example, the period of “*in 1991*” covers the whole 1991. I call adverbials of this kind *period adverbials*.

(2.116) Who was the sales manager in 1991?

(2.117) Did BA737 circle on Monday?

(2.118) Which flights did J.Adams inspect yesterday?

“*Before ...*” and “*after ...*” adverbials (e.g. (2.119)) can also be considered period adverbials, except that in this case one of the boundaries of the period is left unspecified. (I model time as bounded; see section 3.3 below. In the absence of other constraints, I treat the unspecified boundary as the beginning or end of time.) In (2.119), for example, the end of the period is the beginning of 2/5/95; the beginning of the period is left unspecified. “*Before*” and “*after*” can also introduce temporal subordinate clauses; this will be discussed in section 2.10.2.

(2.119) Which company serviced BA737 before 2/5/95?

This thesis examines only period adverbials introduced by “*in*”, “*on*”, “*before*”, and “*after*”, as well as “*today*” and “*yesterday*”. (“*In ...*” adverbials can also specify durations, e.g. “*in two hours*”; this will be discussed in section 2.9.4.) Other period adverbials, like “*from 1989 to 1990*”, “*since 1990*”, “*last week*”, or “*two days ago*”, are not considered. Extending the framework of this thesis to support more period adverbials should not be difficult.

With states: When period adverbials combine with state expressions, the situation of the state expression must hold for at least some time during the period of the adverbial. In (2.120), for example, the person must have been a manager for at least some time in 1995. Similarly, in (2.121), the person must have been at gate 2 for at least some time on the previous day.

(2.120) Who was a manager in 1995?

(2.121) Who was at gate 2 yesterday?

There is often, however, an implication that the situation holds *throughout* the period of the adverbial. (2.122), for example, could mean that the tank was empty throughout January, not at simply some part of January. Similarly, in (2.123) the user could be referring to tanks that were empty *throughout* January. In that case, if a tank was empty only some days in January and the NLITDB included that tank in the answer, the user would be misled to believe that the tank was empty throughout January. Similar comments can be made for (2.124) and (2.125).

(2.122) Tank 4 was empty in January.

(2.123) Which tanks were empty in January?

(2.124) Was runway 2 open on 6/7/95?

(2.125) Which flights departed (habitually) from gate 2 in 1993?

The same implication is possible in sentences with “*before ...*” or “*after ...*” adverbials. (2.126), for example, could mean that the runway was open all the time from some unspecified time up to immediately before 5:00pm (and possibly longer).

(2.126) Runway 2 was open before 5:00pm.

One way to deal with such implications is to treat sentences where period adverbials combine with states as ambiguous. That is, to distinguish between a reading where the situation holds throughout the adverbial’s period, and a reading where the situation holds at simply some part of the adverbial’s period. [Vlach 93] (p. 256) uses the terms *durative* and *inclusive* to refer to the two readings. (A NLITDB could paraphrase both readings and ask the user to select one, or it could provide answers to both readings, indicating which answer corresponds to which reading.) This approach has the disadvantage of always generating two readings, even in cases where the durative

reading is clearly impossible. For example, when the state expression combines not only with a period adverbial but also with a “*for . . .*” duration adverbial, the meaning can never be that the situation must necessarily hold all the time of the adverbial’s period. For example, (2.127) can never mean that the tank must have been empty throughout January (cf. (2.123)).

(2.127) Which tank was empty for two days in January?

(2.128) When on 6/7/95 was tank 5 empty?

Similarly, in time-asking questions like (2.128), the durative reading is impossible. (2.128) can never mean that the tank must have been empty throughout 6/7/95 (cf. (2.124)). Formulating an account of exactly when the durative reading is possible is a task which I have not undertaken. Although in chapter 3 I discuss how the distinction between durative and inclusive readings could be captured in TOP, for simplicity in the rest of this thesis I consider only the inclusive readings, ignoring the durative ones.

With points: When period adverbials combine with point expressions, the period of the adverbial must contain the time where the instantaneous situation of the point expression occurs (e.g. (2.129)).

(2.129) Did BA737 enter sector 5 on Monday?

With culminating activities: When period adverbials combine with culminating activity expressions, I allow two possible readings: (a) that the situation of the culminating activity expression both starts and reaches its completion within the adverbial’s period, or (b) that the situation simply reaches its completion within the adverbial’s period. In the second reading, I treat the culminating activity expression as referring to only the completion of the situation it would normally describe, and the aspectual class is changed to point.

The first reading is the preferred one in (2.130) which is most naturally understood as referring to a runner who both started and finished running the 40 miles on Wednesday (“*to run*” (a distance) is typically classified as culminating activity verb).

(2.130) Who ran 40 miles on Wednesday?

In the airport domain, the first reading is the preferred one in (2.131) (the inspection both started and was completed on Monday).

(2.131) J.Adams inspected BA737 on Monday.

The second reading (the situation simply reaches its completion within the adverbial's period) is needed in questions like (2.132) and (2.133). In the airport domain, “*to land*” and “*to take off*” are culminating activity verbs (landings and taking offs involve following particular procedures; the landing or taking off starts when the pilot starts the corresponding procedure, and is completed when that procedure is completed). If only the first reading were available (both start and completion within the adverbial's period), in (2.132) the NLITDB would report only flights that both started and finished landing on Monday. If a flight started the landing procedure at 23:55 on Sunday and finished it at 00:05 on Monday, that flight would not be reported. This seems over-restrictive. In (2.132) the most natural reading is that the flights must have simply touched down on Monday, i.e. the landing must have simply been completed within Monday. Similar comments can be made for (2.133) and (2.134) (in domains where “*to fix*” is a culminating activity verb).

(2.132) Which flights landed on Monday?

(2.133) Which flights took off after 5:00pm?

(2.134) Did J.Adams fix any faults yesterday?

The problem in these cases is that “*to land*”, “*to take off*”, and “*to fix*” need to be treated as point verbs (referring to only the time-points where the corresponding situations are completed), even though they have been classified as culminating activity verbs (section 2.4.5). The second reading allows exactly this. The culminating activity expression is taken to refer to only the completion point of the situation it would normally describe, its aspectual class is changed to point, and the completion point is required to fall within the adverbial's period.

The fact that two readings are allowed when period adverbials combine with culminating activities means that sentences like (2.131) – (2.134) are treated as ambiguous. In all ambiguous sentences, I assume that a NLITDB would present all readings to the user asking them to choose one, or that it would provide answers to all readings, showing which answer corresponds to which reading. (The prototype NLITDB of this

thesis adopts the second strategy, though the mechanism for explaining which answer corresponds to which reading is primitive: the readings are shown as TOP formulae.)

In the case of “*before ...*” adverbials (e.g. (2.135)), the two readings are semantically equivalent: requiring the situation to simply reach its completion before some time is equivalent to requiring the situation to both start and reach its completion before that time. To avoid generating two equivalent readings, I allow only the reading where the situation both starts and reaches its completion within the adverbial’s period.

(2.135) Which flights took off before 5:00pm?

Even with the second reading, the answers of the NLITDB may not always be satisfactory. Let us assume, for example, that J.Adams started inspecting a flight late on Monday, and finished the inspection early on Tuesday. None of the two readings would include that flight in the answer to (2.136), because both require the completion point to fall on Monday. While strictly speaking this seems correct, it would be better if the NLITDB could also include in the answer inspections that *partially* overlap the adverbial’s period, warning the user about the fact that these inspections are not completely contained in the adverbial’s period. This is another case where cooperative responses (section 1.4) are needed.

(2.136) Which flights did J.Adams inspect on Monday?

Finally, I note that although in the airport domain “*to taxi*” (to destination) is a culminating activity verb, in (2.137) the verb form is a (progressive) state. Hence, the NLITDB’s answer would be affirmative if BA737 was taxiing to gate 2 some time within the adverbial’s period (before 5:00pm), even if BA737 did not reach the gate during that period. This captures correctly the most natural reading of (2.137).

(2.137) Was BA737 taxiing to gate 2 before 5:00pm?

With activities: When period adverbials combine with activities, I require the situation of the verb to hold for at least some time within the adverbial’s period (same meaning as with states). In (2.138), for example, the flight must have circled for at least some time on Monday, and in (2.139) the flights must have taxied for at least some time after 5:00pm.

meanings of period adverbials	
with state or activity	situation holds for at least part of adverbial's period
with culm. activity	situation starts and is completed within adverbial's period, or situation is simply completed within adverbial's period* [†]
with point	instantaneous situation occurs within adverbial's period
*Not with “ <i>before</i> ... ” adverbials.	
[†] The resulting aspectual class is point. (In all other cases the aspectual class remains the same.)	

Table 2.3: Period adverbials in the framework of this thesis

(2.138) Did BA737 circle on Monday?

(2.139) Which flights taxied after 5:00pm?

Another stricter reading is sometimes possible (especially with “*before*” and “*after*”): that the situation does not extend past the boundaries of the adverbial's period. For example, (2.139) would refer to flights that *started* to taxi after 5:00pm (a flight that started to taxi at 4:55pm and continued to taxi until 5:05pm would not be reported). This reading is perhaps also possible with states (e.g. (2.126)), though with activities it seems easier to accept. As a simplification, such readings are ignored in this thesis.

Elliptical forms: “*Before*” and “*after*” are sometimes followed by noun phrases that do not denote entities of the temporal ontology (e.g. (2.140)).

(2.140) Did J.Adams inspect BA737 before/after UK160?

(2.141) Did J.Adams inspect BA737 before/after he inspected UK160?

Questions like (2.140) can be considered elliptical forms of (2.141), i.e. in these cases “*before*” and “*after*” could be treated as when they introduce subordinate clauses (section 2.10.2 below). Questions like (2.140) are currently not supported by the framework of this thesis.

Table 2.3 summarises the main points of this section.

2.9.3 Duration “*for* ... ” adverbials

This section discusses “*for* ... ” adverbials that specify durations (e.g. (2.142)).

(2.142) Runway 2 was open for five days.

With states and activities: When “for ... ” adverbials combine with states or activities, one reading is that there must be a period with the duration of the “for ... ” adverbial, such that the situation of the state or activity holds throughout that period. According to this reading, in (2.143) there must be a five-year period, throughout which the person was a manager, and in (2.143) a twenty-minute period throughout which the flight was circling. If J.Adams was a manager for six consecutive years (e.g. 1981 – 1986), he would be included in the answer to (2.143), because there is a five-year period (e.g. 1981 – 1985) throughout which he was a manager.

(2.143) Who was a manager for five years?

(2.144) Did BA737 circle for twenty minutes?

In some cases, however, “for ... ” adverbials are used with a stricter meaning: they specify the duration of a *maximal* period where a situation held. In that case, if J.Adams started to be a manager at the beginning of 1981 and stopped being a manager at the end of 1986 (six consecutive years), he would *not* be included in the answer to (2.143). For simplicity, this stricter reading is ignored in this thesis .

In other cases, a “for ... ” adverbial does not necessarily specify the duration of a *single* period, but a *total duration*. According to this reading, if J.Adams was a manager during several non-overlapping periods, and the total duration of these periods is five years, he would be included in the answer to (2.143), even if he was never a manager for a continuous five-year period. This reading of “for” adverbials is also not supported in this thesis.

There is a problem if “for ... ” adverbials are allowed to combine with consequent states (section 2.9.1). This problem will be discussed in section 4.11.3, once some formal apparatus has been established. For the moment, I note that the solution involves disallowing “for ... ” adverbials to be used with consequent states.

With points: “For ... ” adverbials sometimes specify the duration of a situation that *follows* the situation of the verb. This is particularly common when “for ... ” adverbials combine with point expressions. For instance, (2.145) (based on an example from [Hwang & Schubert 94]), probably does not mean that J.Adams was actually leaving his office for fifteen minutes. It means that he stayed (or intended to stay) out of his office for fifteen minutes. (I assume here that “to leave” is a point verb, as in

the airport domain.) This use of “for ... ” adverbials is not supported in this thesis.

(2.145) J.Adams left his office for fifteen minutes.

“For ... ” adverbials also give rise to iterative readings (section 2.5.3). This is again particularly common with point expressions. (2.146) (from [Hwang & Schubert 94]) probably means that Mary won several times (“to win” is typically classified as point verb). Such iterative uses of “for ... ” adverbials are not supported in this thesis.

(2.146) Mary won the competition for four years.

Excluding iterative readings and readings where “for ... ” adverbials refer to consequent situations (both are not supported in this thesis), sentences where “for ... ” adverbials combine with point expressions either sound odd or signal that the user is unaware that the situation of the point expression is modelled as instantaneous (an explanatory message to the user is needed in the latter case; this thesis, however, provides no mechanism to generate such messages). Hence, for the purposes of this thesis it seems reasonable not to allow “for ... ” adverbials to combine with point expressions.

With culminating activities: When “for ... ” adverbials combine with culminating activities, the resulting sentences sometimes sound odd or even unacceptable. For example, (2.147) (based on an example from [Moens 87]) sounds odd or unacceptable to most native English speakers (“to build” is typically classified as culminating activity verb). In contrast, (2.148) where the adverbial combines with a (progressive) state is easily acceptable.

(2.147) ?Housecorp built a shopping centre for two years.

(2.148) Housecorp was building a shopping centre for two years.

Based on similar examples, Vendler (section 2.2) concludes that accomplishments (culminating activities) do not combine with “for ... ” adverbials. This, however, seems over-restrictive. (2.149) and (2.150), for example, seem acceptable.

(2.149) BA737 taxied to gate 2 for two minutes.

(2.150) Did J.Adams inspect BA737 for ten minutes?

meanings of duration “for ... ” adverbials	
with lexical or progressive state	situation holds continuously for at least that long
with consequent state	(not allowed in the framework of this thesis)
with activity	situation holds continuously for at least that long
with culminating activity	situation holds continuously for at least that long (no need for climax to be reached)
with point	(not allowed in the framework of this thesis)

Table 2.4: Duration “for ... ” adverbials in the framework of this thesis

Unlike (2.151), in (2.149) there is no requirement that the taxiing must have been completed, i.e. that BA737 must have reached the gate. Similar comments can be made for (2.150) and (2.152). “For ... ” adverbials seem to cancel any requirement that the climax must have been reached. (Similar observations are made in [Dowty 86], [Moens & Steedman 88], and [Kent 93].)

(2.151) BA737 taxied to gate 2.

(2.152) Did J.Adams inspect BA737?

In the framework of this thesis, I allow “for ... ” adverbials to combine with culminating activities, with the same meaning that I adopted in the case of states and activities, and with the proviso that any requirement that the climax must have been reached should be cancelled. That is, in (2.150) there must be a ten-minute period throughout which J.Adams was inspecting BA737.

Table 2.4 summarises the main points of this section.

2.9.4 Duration “in ... ” adverbials

This section discusses “in ... ” adverbials that specify durations (e.g. (2.153), (2.154)). “In” can also introduce period adverbials (e.g. “in 1995”; see section section 2.9.2).

(2.153) Airserve serviced BA737 in two hours.

(2.154) Which flight did J.Adams inspect in one hour?

With culminating activities: With culminating activity expressions, “in ... ” adverbials usually specify the length of a period that ends at the time-point where the situation of the culminating activity expression is completed. In (2.153), for example, two hours is probably the length of a period that ends at the time-point where the

service was completed. (2.154) is similar. The period whose length is specified by the “*in ...*” adverbial usually starts at the time-point where the situation of the culminating activity expression begins. In (2.153), for example, the two hours probably start at the time-point where the service began. The period of the adverbial, however, may sometimes not start at the beginning of the situation of the culminating activity expression, but at some other earlier time. In (2.153), the start of the two hours could be the time-point where Airserve was asked to service BA737, not the beginning of the actual service. The framework of this thesis supports only the case where the period of the adverbial starts at the beginning of the situation described by the culminating activity expression.

With points: With point expressions, the period of the “*in ...*” adverbial starts before the (instantaneous) situation of the point expression, and ends at the time-point where the situation of the point expression occurs. In (2.155) the ten minutes end at the point where BA737 arrived at gate 2, and start at some earlier time-point (e.g. when BA737 started to taxi to gate 2). (2.156) is similar.

(2.155) BA737 reached gate 2 in ten minutes.

(2.156) BA737 entered sector 2 in five minutes.

Determining exactly when the period of the adverbial starts is often difficult. It is not clear, for example, when the five minutes of (2.156) start. As a simplification, I do not allow duration “*in ...*” adverbials to combine with point expressions.

With states and activities: “*In ...*” adverbials are sometimes used with activity expressions, with the “*in ...*” duration adverbial intended to specify the duration of the situation described by the activity expression. Typically, in these cases the speaker has a culminating activity view in mind. For example, (2.157) can be used in this way if the speaker has a particular destination (say gate 2) in mind. In that case, (2.157) can be thought as an elliptical form of (2.158). The framework of this thesis does not support this use of (2.157).

(2.157) BA737 taxied in ten minutes.

(2.158) BA737 taxied to gate 2 in ten minutes.

meanings of duration “in ... ” adverbials	
with state, activity, or point	(not allowed in the framework of this thesis)
with culminating activity	distance from the start to the completion of the situation

Table 2.5: Duration “in ... ” adverbials in the framework of this thesis

With state and activity expressions, “in ... ” adverbials can also specify the duration of a period that ends at the beginning of the situation of the state or activity expression. In (2.159), for example, the two hours probably end at the time-point where tank 5 started to be empty. The beginning of the two hours could be, for example, a time-point where a pump started to empty the tank, or a time-point where a decision to empty the tank was taken. Similar comments apply to (2.157).

(2.159) Tank 5 was empty in two hours.

As with point expressions, determining exactly when the period of the adverbial starts is often difficult. As a simplification, I do not allow duration “in ... ” adverbials to combine with state or activity expressions.

Table 2.5 summarises the main points of this section.

2.9.5 Other temporal adverbials

Other temporal adverbials, that are not supported by the framework of this thesis, include some adverbials that specify boundaries (e.g. “until 1/5/95”, “since 1987”, “by Monday”), frequency adverbials (“always”, “twice”, “every Monday”), and adverbials of temporal order (“for the second time”, “earlier”).

2.10 Temporal subordinate clauses

Three kinds of temporal subordinate clauses are examined in this thesis: clauses introduced by “while”, “before”, and “after” (e.g. clauses introduced by “since”, “until”, or “when” are not examined). From the temporal subordinate clauses that are not examined, “when ... ” clauses are generally considered the most difficult to support (see [Ritchie 79], [Yip 85], [Hinrichs 86], [Moens 87], [Moens & Steedman 88], and [Lascarides & Oberlander 93] for explorations of “when ... ” clauses).

2.10.1 “While ... ” clauses

Subordinate clause: As with period adverbials (section 2.9.2), each “while ... ” clause is understood as specifying a time period. This is a maximal period throughout which the situation of the “while ... ” clause holds. Let us assume, for example, that J.Adams was a manager only from 1/1/1980 to 31/12/1983, and from 1/1/1987 to 31/12/1990. Then, in (2.160) the period of the “while ... ” clause can be either one of these two periods. The user may have in mind a particular one of the two periods. In that case, a temporal anaphora resolution mechanism is needed to determine that period (temporal anaphora is discussed in section 2.12). The framework of this thesis, however, provides no such mechanism (the answer to (2.160) includes anybody who was fired during any of the two periods).

(2.160) Who was fired while J.Adams was a manager?

Sentences where the aspectual class of the “while ... ” clause is point (e.g. (2.161) in the airport domain) typically signal that the user is unaware that the situation of the “while ... ” clause is modelled as instantaneous. In the framework of this thesis, the answer to (2.161) includes any flight that was circling at the time-point where BA737 entered sector 2. Ideally, a message would also be generated to warn the user that entering a sector is modelled as instantaneous (no warning is currently generated). This is another case where cooperative responses (section 1.4) are needed.

(2.161) Which flights were circling while BA737 entered sector 2?

Sentences containing “while ... ” clauses whose aspectual class is consequent state (section 2.9.1) usually sound unnatural or unacceptable. For example, (2.162) – (2.164) sound at least unnatural (e.g. instead of (2.162) one would normally use (2.165) or (2.166)). Hence, I do not allow “while ... ” clauses whose aspectual class is consequent state. This also avoids some complications in the English to TOP mapping.

(2.162) ?Did any flight depart while BA737 had landed?

(2.163) ?Did ABM fire anybody while J.Adams had been the manager?

(2.164) ?Had any flight departed while J.Adams had inspected BA737?

(2.165) Did any flight depart while BA737 was landing?

(2.166) Did any flight depart after BA737 had landed?

aspectual class of “while ... ” clause	period specified by “while ... ” clause
consequent state	(not allowed in the framework of this thesis)
lexical/progressive state or activity	maximal period where situation of “while ... ” clause holds
culminating activity	maximal period where situation of “while ... ” clause holds (no need for climax of “while ... ” clause to be reached)
point	instant. period where situation of “where ... ” clause occurs

Table 2.6: Periods of “while ... ” clauses in the framework of this thesis

When the aspectual class of the “while ... ” clause is culminating activity, there is no requirement that the climax of the situation of the “while ... ” clause must have been reached, even if the tense of that clause normally requires this. In (2.168) and (2.171), for example, there does not seem to be any requirement that the service or the boarding must have been completed (cf. (2.167) and (2.170)). (2.168) and (2.171) appear to have the same meanings as (2.169) and (2.172) (in progressive tenses, there is no requirement for the climax to be reached; see section 2.5.3).

Table 2.6 summarises the main points about “while ... ” clauses so far.

- (2.167) Did Airserve service BA737?
 (2.168) Which flights departed while Airserve serviced BA737?
 (2.169) Which flights departed while Airserve was servicing BA737?
 (2.170) Did BA737 board?
 (2.171) Which flights departed while BA737 boarded?
 (2.172) Which flights departed while BA737 was boarding?

Main clause: Once the periods of the “while ... ” clauses have been established (following table 2.6), the behaviour of “while ... ” clauses appears to be the same as that of period adverbials (i.e. it follows table 2.3 on page 49). With main clauses whose aspectual class is point, the instantaneous situation of the main clause must occur within the period of the “while ... ” clause (e.g. in (2.173) the departures must have occurred during a maximal period where runway 5 was closed; “to depart” is a point verb in the airport domain).

- (2.173) Did any flight depart from gate 2 while runway 5 was closed?

With activity main clauses, the situation of the main clause must be ongoing some time during the period of the “*while ...*” clause. In (2.174), for example, the flights must have taxied some time during a maximal period where BA737 was circling. As with period adverbials, stricter readings are sometimes possible with activity main clauses. (2.174), for example, could refer to flights that both started and stopped taxiing during a maximal period where BA737 was circling. As with period adverbials, I ignore such stricter readings.

(2.174) Which flights taxied while BA737 circled?

As in the case of period adverbials, with culminating activity main clauses I allow two readings: (a) that the situation of the main clause both starts and reaches its completion within the period of the “*while ...*” clause, or (b) that the situation of the main clause simply reaches its completion within the period of the “*while ...*” clause. In the second reading, the main clause is taken to refer to only the completion point of the situation it would normally describe, and its aspectual is changed to point. In the airport domain, the first reading is the preferred one in (2.175). The second reading allows the answer to (2.176) to contain flights that simply touched down during the service, even if their landing procedures did not start during the service.

(2.175) J.Adams inspected BA737 while Airserve was servicing UK160.

(2.176) Which flights landed while Airserve was servicing UK160?

With state main clauses, I require the situation of the main clause to hold some time during the period of the “*while ...*” clause (inclusive reading; see section 2.9.2). For example, the answer to (2.177) must contain anybody who was a lecturer some time during a maximal period where J.Adams was a professor (the non-auxiliary “*to be*” is typically classified as state verb). As with period adverbials, there is often an implication that the situation of the main clause holds *throughout* the period of the “*while ...*” clause (durative reading). The durative reading is unlikely in (2.177), but seems the preferred one in (2.178) (progressive state main clause). According to the durative reading, (2.178) refers to a flight that was circling *throughout* a maximal period where runway 2 was closed.

(2.177) Who was a lecturer while J.Adams was a professor?

(2.178) Which flight was circling while runway 2 was closed?

The treatment of “*while ...*” clauses of this thesis is similar to that of [Ritchie 79]. Ritchie also views “*while ...*” clauses as establishing periods, with the exact relations between these periods and the situations of the main clauses depending on the aspectual classes of the main clauses. Ritchie uses only two aspectual classes (“continuing” and “completed”), which makes presenting a direct comparison between his treatment of “*while ...*” clauses and the treatment of this thesis difficult. Both approaches, however, lead to similar results, with the following two main exceptions. (a) In (2.177) and (2.178) (state main clause), Ritchie’s treatment admits only durative readings. In contrast, the framework of this thesis admits only inclusive ones. (b) In (2.176) (culminating activity main clause), Ritchie’s arrangements allow only one reading, where the landings must have both started and been completed during the service. The framework of this thesis allows an additional reading, whereby it is enough if the landings were simply completed during the service.

2.10.2 “*Before ...*” and “*after ...*” clauses

I treat “*before ...*” and “*after ...*” clauses as establishing periods, as in the case of the “*before ...*” and “*after ...*” adverbials of section 2.9.2. In “*before ...*” clauses, the period starts at some unspecified time-point (in the absence of other constraints, the beginning of time), and ends at a time-point provided by the “*before ...*” clause. In “*after ...*” clauses, the period starts at a time-point provided by the “*after ...*” clause, and ends at some unspecified time-point (the end of time, in the absence of other constraints). I use the terms *before-point* and *after-point* to refer to the time-points provided by “*before ...*” and “*after ...*” clauses respectively. Once the periods of the “*before ...*” and “*after ...*” clauses have been established, the behaviour of the clauses appears to be the same as that of period adverbials (i.e. it follows table 2.3 on page 49).

State “*before/after ...*” clause: Let us first examine sentences where the aspectual class of the “*before ...*” or “*after ...*” clause is state. With “*before ...*” clauses, the before-point is a time-point where the situation of the “*before ...*” clause starts (table 2.7). In (2.179), for example, the before-point is a time-point where runway 2 started to be open. The aspectual class of the main clause is point (“*to depart*” is a point verb in the airport domain). Hence, according to table 2.3 on page 49, the

aspectual class of “before ... ” clause	before-point (right boundary of period specified by “before ... ” clause)
state	time-point where situation of “before ... ” clause starts
activity	time-point where situation of “before ... ” clause starts
culm. activity	time-point where situation of “before ... ” clause starts or is completed
point	time-point where situation of “before ... ” clause occurs

Table 2.7: Boundaries of “before ... ” clauses in the framework of this thesis

departures must have occurred within the period of the “before ... ” clause, i.e. before the time-point where runway 2 started to be open. Similar comments apply to (2.180), (2.181) (progressive “before ... ” clause), and (2.182) (consequent state “before ... ” clause). In (2.182), the before-point is the beginning of the consequent period of the inspection (the period that contains all the time after the completion of the inspection; see section 2.9.1), i.e. the departures must have happened before the inspection was completed.

(2.179) Which flights departed before runway 2 was open?

(2.180) Which flights departed before the emergency system was in operation?

(2.181) Which flights departed before BA737 was circling?

(2.182) Which flights departed before J.Adams had inspected BA737?

According to table 2.3 on page 49, in (2.183) where the main clause is a state, the flight must have been at gate 2 some time during the period of the “before ... ” clause, i.e. for some time before runway 2 started to be open. In (2.184) (activity main clause), the flight must have circled for some time before runway 2 started to be open, and in (2.185) (culminating activity main clause) the inspections must have both started and been completed before runway 2 started to be open. (As with the “before ... ” adverbials of section 2.9.2, in (2.185) it would be better if the NLITDB could also report inspections that started but were not completed before runway 2 opened, warning the user that these inspections were not completed before runway 2 opened.)

(2.183) Was any flight at gate 2 before runway 2 was open?

(2.184) Did any flight circle before runway 2 was open?

(2.185) Which flights did J.Adams inspect before runway 2 was open?

aspectual class of “before ... ” clause	after-point (left boundary of period specified by “after ... ” clause)
lexical/progressive state	time-point where situation of “after ... ” clause starts or ends
consequent state	time-point where consequent period of “after ... ” clause starts
activity	time-point where situation of “after ... ” clause ends
culm. activity	time-point where situation of “after ... ” clause is completed
point	time-point where situation of “before ... ” clause occurs

Table 2.8: Boundaries of “after ... ” clauses in the framework of this thesis

In the case of “after ... ” clauses, when the aspectual class of the “after ... ” clause is state, the after-point is a time-point where the situation of the “after ... ” clause either starts or ends. (2.186), for example, has two readings: that the flights must have departed after runway 2 *started* to be open, or that the flights must have departed after runway 2 *stopped* being open. Similar comments apply to (2.187) and (2.188).

(2.186) Which flights departed after runway 2 was open?

(2.187) Which flights departed after the emergency system was in operation?

(2.188) Which flights departed after BA737 was circling?

In sentences like (2.189), where the aspectual class of the “after ... ” clause is consequent state, the after-point can only be the beginning of the consequent period (the first time-point after the completion of the inspection). It cannot be the end of the consequent period: the end of the consequent period is the end of time; if the after-point were the end of the consequent period, the departures of (2.189) would have to occur after the end of time, which is impossible. This explains the distinction between lexical/progressive and consequent states in table 2.8.

(2.189) Which flights departed after J.Adams had inspected BA737?

Point “before/after ... ” clause: If the aspectual class of the “before ... ” or “after ... ” clause is point, the before/after-point is the time-point where the instantaneous situation of the subordinate clause occurs. In (2.190), for example, the before/after-point is the point where BA737 reached gate2.

(2.190) Which flights departed before/after BA737 reached gate 2?

Activity “before/after ... ” clause: With activity “before/after ... ” clauses, I consider the before-point to be a time-point where the situation of the “before ... ” clause starts, and the after-point to be a point where the situation of the “after ... ” clause ends. In (2.191) and (2.192), for example, the departures must have occurred before BA737 *started* to taxi or circle. In (2.193) and (2.194), the departures must have occurred after BA737 *stopped* taxiing or circling.

(2.191) Which flights departed before BA737 taxied?

(2.192) Which flights departed before BA737 circled?

(2.193) Which flights departed after BA737 taxied?

(2.194) Which flights departed after BA737 circled?

Perhaps another reading is sometimes possible with “after ... ” clauses: that the after-point is a time-point where the situation of the “after ... ” clause *starts* (e.g. (2.194) would refer to departures that occurred after BA737 *started* to circle). This reading, however, does not seem very likely, and for simplicity I ignore it.

Culminating activity “before/after ... ” clause: With “after ... ” clauses whose aspectual class is culminating activity, I consider the after-point to be a time-point where the situation of the “after ... ” clause reaches its completion. In (2.195), the departures must have occurred after the completion of the inspection, and in (2.196) they must have occurred after the time-point where BA737 reached gate 2.

(2.195) Which flights departed after J.Adams inspected BA737?

(2.196) Which flights departed after BA737 taxied to gate 2?

With culminating activity “before ... ” clauses, I allow the before-point to be a time-point where the situation of the “before ... ” clause either starts or reaches its completion. In the airport domain, the first reading seems the preferred one in (2.197) (the flights must have departed before the *beginning* of the inspection). The second reading seems the preferred one in (2.199) (the flights must have departed before the *completion* of the landing). Both readings seems possible in (2.199).

(2.197) Which flights departed before J.Adams inspected BA737?

(2.198) Which flights departed before BA737 landed?

(2.199) Which flights departed before BA737 taxied to gate 2?

If the first reading is adopted (the situation of the “*before ...*” clause *starts* at the before-point) and the “*before ...*” clause is in the simple past, it is unclear if the situation of the “*before ...*” clause must have necessarily reached its climax (the simple past of culminating activity verbs normally requires this; see section 2.5.2). For example, let us assume that the first reading is adopted in (2.197). Should the before-point be the beginning of an inspection that was necessarily completed, or can it also be the beginning of an inspection that was never completed? The framework of this thesis currently adopts the first approach, but this is perhaps over-restrictive. It would probably be better if the NLITDB allowed the before-point to be the beginning of both inspections that were and were not completed, warning the user about inspections that were not completed. This is another case for cooperative responses (section 1.4).

Other uses: “*Before*” and “*after*” can be preceded by expressions specifying durations (e.g. (2.200)). This use of “*before*” and “*after*” is not considered in this thesis.

(2.200) BA737 reached gate 2 five minutes after UK160 departed.

“*Before ...*” clauses also have counter-factual uses. For example, in (2.201) (from [Crouch 91]) the situation where the car runs into the tree never takes place. This use of “*before*” is not considered in this thesis.

(2.201) Smith stopped the car before it ran into the tree.

The treatment of “*before ...*” and “*after ...*” clauses of this thesis is similar to that of [Ritchie 79]. Ritchie also views “*before ...*” and “*after ...*” clauses as providing before and after-points. As noted in section 2.10.1, however, Ritchie uses only two aspectual classes. According to Ritchie, in the case of “*before ...*” clauses, the before-point is a time-point where the situation of the “*before ...*” clause starts, and the situation of the main clause must simply start before that point. In (2.185), this requires the inspections to have simply *started* before the time-point where runway 2 started to be open. In contrast, the framework of this thesis requires the inspections to have been *completed* before that time-point.

In the case of “*after ...*” clauses, the main difference between Ritchie’s treatment and the treatment of this thesis concerns state “*after ...*” clauses. In that case, Ritchie

allows the after-point to be only the beginning of the situation of the “*after ...*” clause. In (2.187), this requires the flights to have departed after the time-point where the system *started* to be in operation. The framework of this thesis allows an additional reading, where the flights must have departed after the time-point where the system *stopped* being in operation.

2.10.3 Tense coordination

Some combinations of tenses in the main and subordinate clauses are unacceptable (e.g. (2.202), (2.203)). This thesis makes no attempt to account for the unacceptability of such combinations. The reader is referred to [Harper & Charniak 86] and [Brent 90] for methods that could be used to detect and reject sentences like (2.202) and (2.203).

(2.202) *BA737 left gate 2 before runway 2 is free.

(2.203) *Which runways are closed while runway 2 was circling?

2.11 Noun phrases and temporal reference

A question like (2.204) can refer either to the present sales manager (asking the 1991 salary of the present sales manager) or to the 1991 sales manager (asking the 1991 salary of the 1991 sales manager). Similarly, (2.205) may refer either to present students or last year’s students. In (2.206), “*which closed runway*” probably refers to a runway that is *currently* closed, while in (2.207) “*a closed runway*” probably refers to a runway that was closed at the time of the landing.

(2.204) What was the salary of the sales manager in 1991?

(2.205) Which students failed in physics last year?

(2.206) Which closed runway was open yesterday?

(2.207) Did BA737 ever land on a closed runway in 1991?

It seems that noun phrases (e.g. “*the sales manager*”, “*which students*”, “*a closed runway*”) generally refer either to the present or to the time of the verb tense (if this time is different than the present). In (2.204), the simple past tense refers to some time in 1991. Therefore, there are two options: “*the sales manager*” can refer either to the present sales manager or to somebody who was the sales manager in 1991. Similar

comments apply to (2.205). In contrast, in (2.208) the verb tense refers to the present. Hence, there is only one possibility: “*the sales manager*” refers to the present sales manager.

(2.208) What is the salary of the sales manager?

In (2.206), the verb tense refers to a time (within the previous day) where the runway was open. There should be two readings: it should be possible for “*which closed runway*” to refer either to a currently closed runway, or to a runway that was closed at the time it was open. Since a runway cannot be closed at the same time where it is open, the second reading is ruled out. (This clash, however, cannot be spotted easily by a NLITDB without some inferential capability.)

The hypothesis that noun phrases refer either to the present or to the time of the verb tense is not always adequate. For example, a person submitting (2.209) to the NLITDB of a university most probably refers to *previous* students of the university. In contrast, the hypothesis predicts that the question can refer only to *current* students. (Similar examples can be found in [Enc 86].)

(2.209) How many of our students are now professors?

The hypothesis also predicts that (2.210) can refer only to current Prime Ministers or to persons that were Prime Ministers at the time they were born (an extremely unlikely reading). There is, however, a reading where the question refers to all past and present Prime Ministers. This reading is incorrectly ruled out by the hypothesis.

(2.210) Which Prime Ministers were born in Scotland?

Hinrichs [Hinrichs 88] argues that determining the times to which noun phrases refer is part of a more general problem of determining the entities to which noun phrases refer. According to Hinrichs, a noun phrase like “*every admiral*” generally refers to anybody who was, is, or will be an admiral of any fleet in the world at any time. If, however, (2.211) is uttered in a context where the current personnel of the U.S. Pacific fleet is being discussed, the temporal scope of “*every admiral*” is restricted to current admirals, in the same way that the scope of “*every admiral*” is restricted to admirals of the U.S. Pacific fleet (e.g. (2.211) does not mean that all Russian admirals also graduated from Annapolis).

(2.211) Every admiral graduated from Annapolis.

The fact that Hinrichs does not limit the times of the noun phrases to the present and the time of the verb tense is in accordance with the fact that “*our students*” in (2.209) is not limited to present students, and the fact that “*which Prime Ministers*” in (2.210) may refer to all past and present Prime Ministers. Hinrichs’ approach, however, requires some mechanism to restrict the scope of noun phrases as the discourse evolves. Hinrichs offers only a very limited sketch of how such a mechanism could be constructed. Also, in the absence of previous discourse, Hinrichs’ treatment suggests that (2.204) refers to the sales managers of all times, an unlikely interpretation. The hypothesis that noun phrases refer either to the present or to the time of the verb tense performs better in this case. Given these deficiencies of Hinrichs’ approach, I adopt the initial hypothesis that noun phrases refer to the present or the time of the verb tense. (An alternative approach would be to attempt to merge this hypothesis with Hinrichs’ method. [Dalrymple 88] goes towards this direction.)

A further improvement can be made to the hypothesis that noun phrases refer to the present or the time of the verb tense. When a noun phrase is the complement of the predicative “*to be*”, it seems that the noun phrase can refer only to the time of the verb tense. (2.212), for example, can only be a request to report the 1991 sales manager, not the current sales manager. Similarly, (2.213) cannot mean that J.Adams is the current sales manager. This also accounts for the fact that in (2.204), unlike “*the sales manager*” which can refer either to the present or 1991, “*the salary of the sales manager*” (the complement of “*was*”) can refer only to a 1991 salary, not to a present salary. (I assume that the restriction that the complement of the predicative “*to be*” must refer to the time of the verb tense does not extend to noun phrases that are constituents of that complement, like “*the sales manager*” in (2.204).) The same restriction applies to bare adjectives used as complements of the predicative “*to be*”. In (2.206), for example, “*open*” can only refer to runways that were open on the previous day. It cannot refer to currently open runways.

(2.212) Who was the sales manager in 1991?

(2.213) J.Adams was the sales manager in 1991.

The hypothesis that noun phrases refer to the present or the time of the verb tense does not apply when a temporal adjective (e.g. “*current*”) specifies explicitly the time

of the noun phrase (e.g. (2.214)). (Although temporal adjectives are not considered in this thesis, I support “*current*” to be able to illustrate this point.)

(2.214) Which current students failed in Physics last year?

In chapter 4, an additional mechanism will be introduced, that allows the person configuring the NLITDB to force some noun phrases to be treated as always referring to the time of the verb tense, or as always referring to the present.

2.12 Temporal anaphora

There are several English expressions (e.g. “*that time*”, “*the following day*”, “*then*”, “*later*”) that refer implicitly to contextually salient times, in a way that is similar to how pronouns, possessive determiners, etc. refer to contextually salient world entities (the terms *temporal* and *nominal anaphora* were used in section 1.4 to refer to these two phenomena; the parallels between temporal and nominal anaphora are discussed in [Partee 84]). For example, the user of a NLITDB may submit (2.215), followed by (2.216). In (2.216), “*at that time*” refers to the time when John became manager (temporal anaphora). In a similar manner, “*he*” refers to John (nominal anaphora).

(2.215) When did John become manager?

(2.216) Was he married at that time?

Names of months, days, etc. often have a similar temporal anaphoric nature. For example, in a context where several questions about the 1990 status of a company have just been asked, (2.217) most probably refers to the January of 1990, not any other January. In the absence of previous questions, (2.217) most probably refers to the January of the current year. (See section 5.5.1 of [Kamp & Reyle 93] for related discussion.)

(2.217) Who was the sales manager in January?

Verb tenses also seem to have a temporal anaphoric nature (the term *tense anaphora* is often used in this case). For example, the user may ask (2.218) (let us assume that the response is “no”), followed by (2.219). In that case, the simple past “*was*” of (2.219) does not refer to an arbitrary past time, it refers to the past time of the previous question, i.e. 1993.

(2.218) Was Mary the personnel manager in 1993?

(2.219) Who was the personnel manager?

The anaphoric nature of verb tenses is clearer in multi-sentence text (see [Hinrichs 86], [Webber 88], [Kamp & Reyle 93], [Kameyama *et al.* 93] for related work). In (2.220), for example, the simple past “*landed*” refers to a landing that happened immediately after the permission of the first sentence was given. It does not refer to an arbitrary past time where BA737 landed on runway 2. Similar comments apply to the “*taxied*”.

(2.220) BA737 was given permission to land at 5:00pm. It landed on runway 2, and taxied to gate 4.

In dialogues like the one in (2.218) – (2.219), a simplistic treatment of tense anaphora is to store the time of the adverbial of (2.218), and to require the simple past of (2.219) to refer to that time. (A more elaborate version of this approach will be discussed in section 3.17.)

The behaviour of noun phrases like “*the sales manager*” of section 2.11 can be seen as a case of temporal anaphora. This is the only type of temporal anaphora that is supported by the framework of this thesis. Expressions like “*at that time*”, “*the following day*”, etc. are not supported, and tenses referring to the past are taken to refer to *any* past time. For example, (2.219) is taken to refer to anybody who was the personnel manager at any past time. The reader is also reminded (section 1.4) that nominal anaphora is not considered in this thesis.

2.13 Other phenomena that are not supported

This section discusses some further phenomena that are not supported by the framework of this thesis.

Cardinality and duration questions: Questions about the cardinality of a set or the duration of a situation (e.g. (2.221), (2.222)) are not supported. (TOP is currently not powerful enough to express the meanings of these questions.)

(2.221) How many flights have landed today?

(2.222) For how long was tank 2 empty?

Cardinalities and plurals: Expressions specifying cardinalities of sets (e.g. “*eight passengers*”, “*two airplanes*”) are not supported (this does not include duration expressions like “*five hours*”, which are supported). Expressions of this kind give rise to a distinction between *distributive* and *collective* readings [Stirling 85] [Crouch & Pulman 93]. (2.223), for example, has a collective reading where the eight passengers arrive at the same time, and a distributive one where there are eight separate arrivals. This distinction was not explored during the work of this thesis. TOP is also currently not powerful enough to express cardinalities of sets.

(2.223) Eight passengers arrived.

The framework of this thesis accepts plural noun phrases introduced by “*some*” and “*which*” (e.g. “*some flights*”, “*which passengers*”), but it treats them semantically as singular. For example, (2.224) and (2.226) are treated as having the same meanings as (2.225) and (2.227) respectively.

(2.224) Which flights landed?

(2.225) Which flight landed?

(2.226) Some flights entered sector 2.

(2.227) A flight entered sector 2.

Quantifiers: Expressions introducing universal quantifiers at the logical level (e.g. “*every*”, “*all*”) are not supported. This leaves only existential quantifiers (and an interrogative version of them, to be discussed in chapter 3) at the logical level, avoiding issues related to quantifier scoping (see also section 6.6.2). It also simplifies the semantics of TOP and the mapping from TOP to TSQL2.

Conjunction, disjunction, and negation: Conjunctions of words or phrases are not supported. Among other things, this avoids phenomena related to sequencing of events. For example, (2.228) is understood as saying that the patient died *after* (and probably as a result of) being given Qdrug (cf. (2.229) which sounds odd). In contrast, in (2.230) the patient was given Qdrug *while* he had high fever. (See, for example, [Hinrichs 86], [Hinrichs 88], [Webber 88], [Kamp & Reyle 93], [terMeulen 94], and [Hwang & Schubert 94] for related work.)

(2.228) Which patient was given Qdrug and died?

(2.229) ?Which patient died and was given Qdrug?

(2.230) Which patient had high fever and was given Qdrug?

Expressions introducing disjunction or negation (e.g. “or”, “either”, “not”, “never”) are also not supported. This simplifies the semantics of TOP and the TOP to TSQL2 mapping. Not supporting negation also avoids various temporal phenomena related to negation (see section 5.2.5 of [Kamp & Reyle 93]), and claims that negation causes aspectual shifts (see, for example, [Dowty 86] and [Moens 87]).

Relative clauses: Relative clauses are also not supported. Relative clauses require special temporal treatment. (2.231), for example, most probably does not refer to a runway that was closed at an *arbitrary* past time; it probably refers to a runway that was closed at the time of the landing. The relation between the time of the relative clause and that of the main clause can vary. In (2.232) (from [Dowty 86]), for example, the woman may have seen John during, before, or even after the stealing.

(2.231) Which flight landed on a runway that was closed?

(2.232) The woman that stole the book saw John.

Relative clauses can also be used with nouns that refer to the temporal ontology (e.g. “period” in (2.233)). Additional temporal phenomena involving relative clauses are discussed in section 5.5.4.2 of [Kamp & Reyle 93].

(2.233) Who was fired during the period that J.Adams was personnel manager?

Passives: Finally, I have concentrated on active voice verb forms. This simplifies the HPSG grammar of chapter 4. It should be easy to extend the framework of this thesis to cover passive forms as well.

2.14 Summary

The framework of this thesis uses an aspectual taxonomy of four classes (states, points, activities, and culminating activities). This taxonomy classifies verb forms,

verb phrases, clauses, and sentences. Whenever the NLITDB is configured for a new application, the base form of each verb is assigned to one of the four aspectual classes. All other verb forms normally inherit the aspectual class of the base form. Verb phrases, clauses, and sentences normally inherit the aspectual classes of their main verb forms. Some linguistic mechanisms (e.g. progressive tenses, or some temporal adverbials), however, may cause the aspectual class of a verb form to differ from that of the base form, or the aspectual class of a verb phrase, clause, or sentence to differ from that of its main verb form. The aspectual taxonomy plays an important role in most time-related linguistic phenomena.

Six tenses (simple present, simple past, present continuous, past continuous, present perfect, and past perfect) are supported, with various simplifications introduced in their meanings. Some special temporal verbs were identified (e.g. “*to happen*”, “*to start*”); from these only “*to start*”, “*to begin*”, “*to stop*”, and “*to finish*” are supported.

Some nouns have a special temporal nature. For example, some introduce situations (e.g. “*inspection*”), others specify temporal order (e.g. “*predecessor*”), and others refer to entities of the temporal ontology (e.g. “*day*”, “*period*”, “*event*”). From all these, only nouns like “*year*”, “*month*”, “*day*”, etc. (and proper names like “*Monday*”, “*January*”, and “*1/5/92*”) are supported. Nouns referring to more abstract temporal entities (e.g. “*period*”, “*event*”) are not supported. No temporal adjectives (e.g. “*first*”, “*earliest*”) are handled, with the only exception of “*current*” which is supported to demonstrate the anaphoric behaviour of some noun phrases.

Among temporal adverbials, only punctual adverbials (e.g. “*at 5:00pm*”), “*for . . .*” and “*in . . .*” duration adverbials, and period adverbials introduced by “*on*”, “*in*”, “*before*”, or “*after*”, as well as “*today*” and “*yesterday*” are handled. Frequency, order, or other adverbials that specify boundaries (e.g. “*twice*”, “*for the second time*”, “*since 1992*”) are not supported.

Only subordinate clauses introduced by “*while*”, “*before*”, and “*after*” are handled (e.g. clauses introduced by “*when*” or “*since*” and relative clauses are not supported). The issue of tense coordination between main and subordinate clauses is ignored.

Among temporal anaphora phenomena, only the temporal anaphoric nature of noun phrases like “*the sales manager*” is supported. Proper names like “*May*” or “*Monday*” are taken to refer to *any* May or Monday. Similarly, past tenses are treated as referring

to *any* past time. Temporal anaphoric expressions like “*that time*” or “*the following day*” are not allowed. (Nominal anaphoric expressions, e.g. “*he*”, “*her salary*”, are also not allowed.)

The framework of this thesis does not support cardinality or duration queries (“*How many . . . ?*”, “*How long . . . ?*”) and cardinality expressions (e.g. “*five flights*”). Plurals introduced by “*which*” and “*some*” (e.g. “*which flights*”, “*some gates*”) are treated semantically as singular. Conjunctions of words or phrases, and expressions introducing universal quantifiers, disjunction, or negation are also not supported. Finally, only active voice verb forms have been considered, though it should be easy to extend the mechanisms of this thesis to support passive voice as well.

Table 2.9 summarises the linguistic coverage of the framework of this thesis.

verb tenses	✓ simple present (excluding scheduled meaning) ✓ simple past ✓ present continuous (excluding futurate meaning) ✓ past continuous (excluding futurate meaning) ✓ present perfect (treated as simple past) ✓ past perfect × other tenses
temporal verbs	✓ “to start”, “to begin”, “to stop”, “to finish” × other temporal verbs (e.g. “to happen”, “to follow”)
temporal nouns	✓ “year”, “month”, “day”, etc. × “period”, “event”, “time”, etc. × nouns introducing situations (e.g. “inspection”) × nouns of temporal order (e.g. “predecessor”)
temporal adjectives	× (only “current”)
temporal adverbials	✓ punctual adverbials (e.g. “at 5:00pm”) ✓ period adverbials (only those introduced by “on”, “in”, “before”, or “after”, and “today”, “yesterday”) ✓ “for ... ” adverbials ✓ “in ... ” duration adverbials (only with culm. act. verbs) × frequency adverbials (e.g. “twice”) × order adverbials (e.g. “for the second time”) × other boundary adverbials (e.g. “since 1987”)
subordinate clauses	✓ “while ... ” clauses ✓ “before ... ” clauses ✓ “after ... ” clauses × relative clauses × other subordinate clauses (e.g. introduced by “when”) × tense coordination between main-subordinate clauses
anaphora	✓ noun phrases and temporal reference × “January”, “August”, etc. (taken to refer to any January, August, etc.) × tense anaphora (past tenses taken to refer to any past time) × “that time”, “the following day”, etc. × nominal anaphora (e.g. “he”, “her salary”)
other phenomena	× cardinality and duration queries (“How many ... ?”, “How long ... ?”) × cardinality expressions (e.g. “five flights”) × plurals (treated as singulars) × conjunctions of words or phrases × expressions introducing universal quantifiers, disjunction, negation × passive voice

Table 2.9: The linguistic coverage of the framework of this thesis

Chapter 3

The TOP Language

“Time will tell.”

3.1 Introduction

This chapter defines TOP, the intermediate representation language of this thesis. As noted in section 1.2.3, TOP employs temporal operators. (3.1), for example, is represented in TOP as (3.2). Roughly speaking, the *Past* operator requires *contain(tank2, water)* to be true at some past time e^v , and the *At* operator requires that time to fall within 1/10/95. The answer to (3.1) is affirmative iff (3.2) evaluates to true.

(3.1) Did tank 2 contain water (some time) on 1/10/95?

(3.2) $At[1/10/95, Past[e^v, contain(tank2, water)]]$

An alternative operator-less approach is to introduce time as an extra argument of each predicate (section 1.2.3). I use temporal operators because they lead to more compact formulae, and because they make the semantic contribution of each linguistic mechanism easier to see (in (3.2), the simple past tense contributes the *Past* operator, while the “on . . . ” adverbial contributes the *At* operator).

TOP is period-based, in the sense that the truth of a TOP formula is checked with respect to a time-period (a segment of the time-axis) rather than an individual time-point. (The term “period” is used here to refer to what other authors call “intervals”; see section 3.3 below.) A TOP formula may be true at a time-period without being true at the subperiods of that period. Actually, following the Reichenbachian tradition

[Reichenbach 47], TOP formulae are evaluated with respect to more than one times: *speech time* (time at which the question is submitted), *event time* (time where the situation described by the formula holds), and *localisation time* (a temporal window within which the event time must be placed; this is different from Reichenbach’s reference time, and similar to the “location time” of [Kamp & Reyle 93]). While speech time is always a time-point, the event and localisation times are generally periods, and this is why I consider TOP period-based. Period-based languages have been used in [Dowty 82], [Allen 84], [Lascarides 88], [Richards *et al.* 89], [Pratt & Bree 95], and elsewhere. Multiple temporal parameters have been used by several researchers (e.g. [Dowty 82], [Hinrichs 88], [Brent 90], [Crouch & Pulman 93]). The term “localisation time” is borrowed from [Crouch & Pulman 93], where *lt* is a temporal window for *et* as in TOP.

Although the aspectual classes of linguistic expressions affect how these expressions are represented in TOP, it is not always possible to tell the aspectual class of a linguistic expression by examining the corresponding TOP formula. The approach here is different from those of [Dowty 77], [Dowty 86], [Lascarides 88], and [Kent 93], where aspectual class is a property of formulae (or denotations of formulae).

TOP was greatly influenced by the representation language of Pirie *et al.* [Pirie *et al.* 90] [Crouch 91] [Crouch & Pulman 93], that was used in a natural language front-end to a planner. TOP, however, differs in numerous ways from the language of Pirie *et al.* (several of these differences will be mentioned in following sections).

3.2 Syntax of TOP

This section defines the syntax of TOP. Some informal comments about the semantics of the language are also given to make the syntax definition easier to follow. The semantics of TOP will be defined formally in following sections.

Terms: Two disjoint sets of strings, *CONS* (constants) and *VARs* (variables), are assumed. I use the suffix “*v*” to distinguish variables from constants. For example, *runway^v*, *gate1^v* \in *VARs*, while *ba737*, *1/5/94* \in *CONS*. *TERMS* (TOP terms) is the set *CONS* \cup *VARs*. (TOP has no function symbols.)

Predicate functors: A set of strings *PFUNS* is assumed. These strings are used as predicate functors (see atomic formulae below).

Complete partitioning names: A set of strings *CPARTS* is assumed. These strings represent *complete partitionings* of the time-axis. A complete partitioning of the time-axis is a set of consecutive non-overlapping periods, such that the union of all the periods covers the whole time-axis. (A formal definition will be given in section 3.4.) For example, the word “*day*” corresponds to the complete partitioning that contains the period that covers exactly the day 13/10/94, the period that covers exactly 14/10/94, etc. No day-period overlaps another one, and together all the day-periods cover the whole time-axis. Similarly, “*month*” corresponds to the partitioning that contains the period for October 1994, the period for November 1994, etc. I use the suffix “*c*” for elements of *CPARTS*. For example, *day^c* could represent the partitioning of day-periods, and *month^c* the partitioning of month-periods.

Gappy partitioning names: A set of strings *GPARTS* is assumed. These strings represent *gappy partitionings* of the time-axis. A gappy partitioning of the time-axis is a set of non-overlapping periods, such that the union of all the periods does *not* cover the whole time-axis. For example, “*Monday*” corresponds to the gappy partitioning that contains the period which covers exactly the Monday 17/10/94, the period that covers exactly the Monday 24/10/94, etc. No Monday-period overlaps another Monday-period, and all the Monday-periods together do not cover the whole time-axis. I use the suffix “*g*” for elements of *GPARTS*. For example, *monday^g* could represent the partitioning of Monday-periods, and *5:00pm^g* the partitioning of all 5:00pm-periods (the period that covers exactly the 5:00pm minute of 24/10/94, the period that covers the 5:00pm minute of 25/10/94, etc.).

Partitioning names: *PARTS* (partitioning names) is the set $CPARTS \cup GPARTS$.

Atomic formulae: *AFORMS* (atomic formulae) is the smallest possible set, such that:

- If $\pi \in PFUNS$, and $\tau_1, \tau_2, \dots, \tau_n \in TERMS$, then $\pi(\tau_1, \tau_2, \dots, \tau_n) \in AFORMS$.

$\pi(\tau_1, \tau_2, \dots, \tau_n)$ is called a *predicate*. $\tau_1, \tau_2, \dots, \tau_n$ are the *arguments* of the predicate.

- If $\sigma \in PARTS$, $\beta \in VARS$, and $\nu_{ord} \in \{\dots, -3, -2, -1, 0\}$, then $Part[\sigma, \beta, \nu_{ord}] \in AFORMS$ and $Part[\sigma, \beta] \in AFORMS$.

Greek letters are used as meta-variables, i.e. they stand for expressions of TOP. Predicates (e.g. $be_at(ba737, gate^v)$) describe situations in the world. $Part[\sigma, \beta, \nu_{ord}]$ means that β is a period in the partitioning σ . The ν_{ord} is used to select a particular period from the partitioning. If $\nu_{ord} = 0$, then β is the current period of the partitioning (the one that contains the present moment). If $\nu_{ord} < 0$, then β is the $-\nu_{ord}$ -th period of the partitioning before the current one. When there is no need to select a particular period from a partitioning, the $Part[\sigma, \beta]$ form is used.

Yes/no formulae: Yes/no formulae represent questions that are to be answered with a “yes” or “no” (e.g. “Is BA737 circling?”). *YNFORMS* is the set of all yes/no formulae. It is the smallest possible set, such that if $\pi \in PFUNS$, $\tau_1, \dots, \tau_n \in TERMS$, $\phi, \phi_1, \phi_2 \in FORMS$, $\sigma_c \in CPARTS$, $\nu_{qty} \in \{1, 2, 3, \dots\}$, β is a TOP variable that does not occur in ϕ , and τ is a TOP variable that does not occur in ϕ or a TOP constant, all the following hold. (The restriction that β and τ must not be variables that occur in ϕ is needed in the translation from TOP to TSQL2 of chapter 5.)

- $AFORMS \subseteq YNFORMS$
- $\phi_1 \wedge \phi_2 \in YNFORMS$
- $Pres[\phi], Past[\beta, \phi], Perf[\beta, \phi] \in YNFORMS$
- $At[\tau, \phi], At[\phi_1, \phi_2] \in YNFORMS$
- $Before[\tau, \phi], Before[\phi_1, \phi_2], After[\tau, \phi], After[\phi_1, \phi_2] \in YNFORMS$
- $Ntense[\beta, \phi], Ntense[now^*, \phi] \in YNFORMS$
- $For[\sigma_c, \nu_{qty}, \phi], Fills[\phi] \in YNFORMS$
- $Begin[\phi], End[\phi] \in YNFORMS$
- $Culm[\pi(\tau_1, \dots, \tau_n)] \in YNFORMS$

No negation and disjunction connectives are defined, because English expressions introducing these connectives are not considered (section 2.13). For the same reason no universal quantifiers are defined. All variables can be thought of as existentially quantified. Hence, no explicit existential quantifier is needed.

An informal explanation of TOP's operators follows (TOP's semantics will be defined formally in following sections). $Pres[\phi]$ means that ϕ is true at the present. For example, "Runway 2 is open." is represented as $Pres[open(runway2)]$. $Past[\beta, \phi]$ means that ϕ is true at some past time β . The $Perf$ operator is used along with the $Past$ operator to express the past perfect. For example, "Runway 2 was open." is represented as $Past[e^v, open(runway2)]$, and "Runway 2 had been open." as:

$$Past[e1^v, Perf[e2^v, open(runway2)]]$$

$At[\tau, \phi]$ means that ϕ holds some time within a period τ , and $At[\phi_1, \phi_2]$ means that ϕ_2 holds at some time where ϕ_1 holds. For example, "Runway 2 was open (some time) on 1/1/94." is represented as $At[1/1/94, Past[e^v, open(runway2)]]$, and "Runway 2 was open (some time) while BA737 was circling." as:

$$At[Past[e1^v, circling(ba737)], Past[e2^v, open(runway2)]]$$

$Before[\tau, \phi]$ means that ϕ is true at some time before a period τ , and $Before[\phi_1, \phi_2]$ means that ϕ_2 is true at some time before a time where ϕ_1 is true. $After[\tau, \phi]$ and $After[\phi_1, \phi_2]$ have similar meanings. For example, "Tank 2 was empty (some time) after 1/1/92." is represented as $After[1/1/92, Past[e^v, empty(tank2)]]$, and "Tank 2 was empty (some time) before the bomb exploded." as:

$$Before[Past[e1^v, explode(bomb)], Past[e2^v, empty(tank2)]]$$

$Ntense$ is used when expressing noun phrases (see section 2.11). $Ntense[\beta, \phi]$ means that at a time β something has the property specified by ϕ . $Ntense[now^*, \phi]$ means that something has the property specified by ϕ at the present. The reading of "The president was visiting Edinburgh." that refers to the person who was the president during the visit is represented as $Ntense[e1^v, president(p^v)] \wedge Past[e1^v, visiting(p^v, edinburgh)]$. In contrast, the reading that refers to the current president is represented as:

$$Ntense[now^*, president(p^v)] \wedge Past[e1^v, visiting(p^v, edinburgh)]$$

$For[\sigma_c, \nu_{qty}, \phi]$ means that ϕ holds throughout a period that is ν_{qty} σ_c -periods long. “Runway 2 was open for two days.” is represented as:

$$For[day^c, 2, Past[e^v, open(runway2)]]$$

The *Fills* operator is currently not used in the framework of this thesis, but it could be used to capture readings of sentences like “Tank 2 was empty in 1992.” whereby the situation of the verb holds *throughout* the period of the adverbial (see section 2.9.2). $At[1992, Past[e^v, Fills[empty(tank2)]]]$ means that the tank was empty *throughout* 1992, while $At[1992, Past[e^v, empty(tank2)]]$ means that the tank was empty some time in 1992, but not necessarily throughout 1992.

$Begin[\phi]$ means that ϕ starts to hold, and $End[\phi]$ means that ϕ stops holding. For example, “BA737 started to land.” can be represented as $Past[e^v, Begin[landing(ba737)]]$, and “Tank 2 stopped being empty.” as $Past[e^v, End[empty(tank2)]]$.

Finally, *Culm* is used to represent sentences where verbs whose base forms are culminating activities appear in tenses that require some inherent climax to have been reached. The *Culm* operator will be discussed in section 3.9.

Wh-formulae: *Wh-formulae* are used to represent questions that contain interrogatives (e.g. “Which ...?”, “Who ...?”, “When ...?”). *WHFORMS* is the set of all wh-formulae. $WHFORMS \stackrel{def}{=} WHFORMS_1 \cup WHFORMS_2$, where:

- $WHFORMS_1$ is the set of all expressions of the form $? \beta_1 ? \beta_2 \dots ? \beta_n \phi$, where $\beta_1, \beta_2, \dots, \beta_n \in VARS$, $\phi \in YNFORMS$, and each one of $\beta_1, \beta_2, \dots, \beta_n$ occurs at least once within ϕ .
- $WHFORMS_2$ is the set of all expressions of the form $?_{mxl} \beta_1 ? \beta_2 ? \beta_3 \dots ? \beta_n \phi$, where $\beta_1, \beta_2, \beta_3, \dots, \beta_n \in VARS$, $\phi \in YNFORMS$, each one of $\beta_2, \beta_3, \dots, \beta_n$ occurs at least once within ϕ , and β_1 occurs at least once within ϕ as the first argument of a *Past*, *Perf*, *At*, *Before*, *After*, or *Ntense* operator, or as the second argument of a *Part* operator.

“?” is the *interrogative quantifier*, and $?_{mxl}$ the *interrogative-maximal quantifier*. The interrogative quantifier is similar to an explicit existential quantifier, but it has the additional effect of reporting the values of its variables that satisfy its scope. Intuitively,

$? \beta_1 ? \beta_2 ? \beta_n \phi$ means “report all $\beta_1, \beta_2, \dots, \beta_n$ such that ϕ ”. For example, “Which runways are open?” is represented as $?r^v \text{Ntense}[\text{now}^*, \text{runway}(r^v)] \wedge \text{Pres}[\text{open}(r^v)]$. The constraint that each one of β_1, \dots, β_n must occur at least once within ϕ rules out meaningless formulae like $?o^v \text{Past}[\text{manager}(\text{john})]$, where the o^v does not have any relation to the rest of the formula. This constraint is similar to the notion of *safety* in DATALOG [Ullman 88], and it is needed in the translation from TOP to TSQL2 of chapter 5.

The interrogative-maximal quantifier is similar, except that it reports only *maximal periods*. $?_{mxl}$ is intended to be used only with variables that denote periods, and this is why in the case of $?_{mxl}$, β_1 is required to occur within ϕ as the first argument of a *Past*, *Perf*, *At*, *Before*, *After*, or *Ntense* operator, or as the second argument of a *Part* operator (the semantics of these operators ensure that variables occurring at these positions denote periods). Intuitively, $?_{mxl} \beta_1 ? \beta_2 ? \beta_n \phi$ means “report all the maximal periods β_1 , and all β_2, \dots, β_n , such that ϕ ”. The interrogative-maximal quantifier is used in “When ... ?” questions, where we want the answer to contain only the *maximal* periods during which a situation held, not all the periods during which the situation held. If, for example, gate 2 was open from 9:00am to 11:00am and from 3:00pm to 5:00pm, we want the answer to “When was gate 2 open?” to contain only the two maximal periods 9:00am to 11:00am and 3:00pm to 5:00pm; we do not want the answer to contain any subperiods of these two maximal periods (e.g. 9:30am to 10:30am). To achieve this, the question is represented as $?_{mxl} e^v \text{Past}[e^v, \text{open}(\text{gate2})]$.

Formulae: *FORMS* is the set of all TOP formulae. $\text{FORMS} \stackrel{\text{def}}{=} \text{YNFORMS} \cup \text{WHFORMS}$.

3.3 The temporal ontology

Point structure: A *point structure* for TOP is an ordered pair $\langle PTS, \prec \rangle$, such that *PTS* is a non-empty set, \prec is a binary relation over $PTS \times PTS$, and $\langle PTS, \prec \rangle$ has the following five properties:

transitivity: If $t_1, t_2, t_3 \in PTS$, $t_1 \prec t_2$, and $t_2 \prec t_3$, then $t_1 \prec t_3$.

irreflexivity: If $t \in PTS$, then $t \prec t$ does not hold.

linearity: If $t_1, t_2 \in PTS$ and $t_1 \neq t_2$, then exactly one of the following holds: $t_1 \prec t_2$ or $t_2 \prec t_1$.

left and right boundedness: There is a $t_{first} \in PTS$, such that for all $t \in PTS$, $t_{first} \preceq t$. Similarly, there is a $t_{last} \in PTS$, such that for all $t \in PTS$, $t \preceq t_{last}$.

discreteness: For every $t_1, t_2 \in PTS$, with $t_1 \neq t_2$, there is at most a finite number of $t_3 \in PTS$, such that $t_1 \prec t_3 \prec t_2$.

Intuitively, a point structure $\langle PTS, \prec \rangle$ for TOP is a model of time. TOP models time as being discrete, linear, bounded, and consisting of time-points (see [vanBenthem 83] for other time models.) PTS is the set of all time-points, and $p_1 \prec p_2$ means that the time-point p_1 precedes the time-point p_2 .

prev(t) and next(t): If $t_1 \in PTS - \{t_{last}\}$, then $next(t_1)$ denotes a $t_2 \in PTS$, such that $t_1 \prec t_2$ and for no $t_3 \in PTS$ is it true that $t_1 \prec t_3 \prec t_2$. Similarly, if $t_1 \in PTS - \{t_{first}\}$, then $prev(t_1)$ denotes a $t_2 \in PTS$, such that $t_2 \prec t_1$ and for no $t_3 \in PTS$ is it true that $t_2 \prec t_3 \prec t_1$. In the rest of this thesis, whenever $next(t)$ is used, it is assumed that $t \neq t_{last}$. Similarly, whenever $prev(t)$ is used, it is assumed that $t \neq t_{first}$.

Periods and instantaneous periods: A *period* p over $\langle PTS, \prec \rangle$ is a non-empty subset of PTS with the following property:

convexity: If $t_1, t_2 \in p$, $t_3 \in PTS$, and $t_1 \prec t_3 \prec t_2$, then $t_3 \in p$.

The term “interval” is often used in the literature instead of “period”. Unfortunately, TSQL2 uses “interval” to refer to a duration (see chapter 5). To avoid confusing the reader when TSQL2 will be discussed, I follow the TSQL2 terminology and use the term “period” to refer to convex sets of time-points.

$PERIODS_{\langle PTS, \prec \rangle}$ is the set of all periods over $\langle PTS, \prec \rangle$. If $p \in PERIODS_{\langle PTS, \prec \rangle}$ and p contains only one time-point, then p is an *instantaneous period* over $\langle PTS, \prec \rangle$. $INSTANTS_{\langle PTS, \prec \rangle}$ is the set of all instantaneous periods over $\langle PTS, \prec \rangle$. For simplicity, I often write $PERIODS$ and $INSTANTS$ instead of $PERIODS_{\langle PTS, \prec \rangle}$ and $INSTANTS_{\langle PTS, \prec \rangle}$, and I often refer to simply “periods” and “instantaneous periods” instead of “periods over $\langle PTS, \prec \rangle$ ” and “instantaneous periods over $\langle PTS, \prec \rangle$ ”.

$PERIODS_{\langle PTS, \prec \rangle}^*$ (or simply $PERIODS^*$) is the set $PERIODS \cup \{\emptyset\}$, i.e. $PERIODS^*$ is the same as $PERIODS$, except that it also contains the empty set. (The reader is reminded that periods are non-empty sets.)

Subperiods: p_1 is a *subperiod* of p_2 , iff $p_1, p_2 \in PERIODS$ and $p_1 \subseteq p_2$. In this case I write $p_1 \sqsubseteq p_2$. ($p_1 \subseteq p_2$ is weaker than $p_1 \sqsubseteq p_2$, because it does not guarantee that $p_1, p_2 \in PERIODS$.) Similarly, p_1 is a *proper subperiod* of p_2 , iff $p_1, p_2 \in PERIODS$ and $p_1 \subset p_2$. In this case I write $p_1 \sqsubset p_2$.

Maximal periods: If S is a set of periods, then $mxlpers(S)$ is the set of *maximal periods* of S . $mxlpers(S) \stackrel{def}{=} \{p \in S \mid \text{for no } p' \in S \text{ is it true that } p \sqsubset p'\}$.

minpt(S) and maxpt(S): If $S \subseteq PTS$, $minpt(S)$ denotes the time-point $t \in S$, such that for every $t' \in S$, $t \preceq t'$. Similarly, if $S \subseteq PTS$, $maxpt(S)$ denotes the time-point $t \in S$, such that for every $t' \in S$, $t' \preceq t$.

Notation: Following standard conventions, $[t_1, t_2]$ denotes the set $\{t \in PTS \mid t_1 \preceq t \preceq t_2\}$. (This is not always a period. If $t_2 \prec t_1$, then $[t_1, t_2]$ is the empty set, which is not a period.) Similarly, $(t_1, t_2]$ denotes the set $\{t \in PTS \mid t_1 \prec t \preceq t_2\}$. $[t_1, t_2)$ and (t_1, t_2) are defined similarly.

3.4 TOP model

A TOP model M is an ordered 7-tuple:

$$M = \langle \langle PTS, \prec \rangle, OBJS, f_{cons}, f_{pfuns}, f_{culms}, f_{gpars}, f_{cpars} \rangle$$

such that $\langle PTS, \prec \rangle$ is a point structure for TOP (section 3.3), $PERIODS_{\langle PTS, \prec \rangle} \subseteq OBJS$, and f_{cons} , f_{pfuns} , f_{culms} , f_{gpars} , and f_{cpars} are as specified below.

OBJS: $OBJS$ is a set containing all the objects in the modelled world that can be denoted by TOP terms. For example, in the airport domain $OBJS$ contains all the gates and runways of the airport, the inspectors, the flights, etc. The constraint $PERIODS_{\langle PTS, \prec \rangle} \subseteq OBJS$ ensures that all periods are treated as world objects. This simplifies the semantics of TOP.

f_{cons}: f_{cons} is a function $CONS \mapsto OBJs$. (I use the notation $D \mapsto R$ to refer to a function whose domain and range are D and R respectively.) f_{cons} specifies which world object each constant denotes. In the airport domain, for example, f_{cons} may map the constants *gate2* and *ba737* to some gate of the airport and some flight respectively.

f_{pfuns}: f_{pfuns} is a function that maps each pair $\langle \pi, n \rangle$, where $\pi \in PFUNS$ and $n \in \{1, 2, 3, \dots\}$, to another function $(OBJs)^n \mapsto pow(PERIODS)$. ($pow(S)$ denotes the powerset of S , i.e. the set of all subsets of S . $(OBJs)^n$ is the n -ary cartesian product $OBJs \times OBJs \times \dots \times OBJs$.) That is, for every $\pi \in PFUNS$ and each $n \in \{1, 2, 3, \dots\}$, $f_{pfuns}(\pi, n)$ is a function that maps each n -tuple of elements of $OBJs$ to a set of periods (an element of $pow(PERIODS)$).

Intuitively, if $\tau_1, \tau_2, \dots, \tau_n$ are TOP terms denoting the world objects o_1, o_2, \dots, o_n , $f_{pfuns}(\pi, n)(o_1, o_2, \dots, o_n)$ is the set of the maximal periods throughout which the situation described by $\pi(\tau_1, \tau_2, \dots, \tau_n)$ is true. For example, if the constant *ba737* denotes a flight-object o_1 , *gate2* denotes a gate-object o_2 , and $be_at(ba737, gate2)$ describes the situation whereby the flight o_1 is located at the gate o_2 , then $f_{pfuns}(be_at, 2)(o_1, o_2)$ will be the set that contains all the maximal periods throughout which the flight o_1 is located at the gate o_2 .

For every $\pi \in PFUNS$ and $n \in \{1, 2, 3, \dots\}$, $f_{pfuns}(\pi, n)$ must have the following property: for every $\langle o_1, o_2, \dots, o_n \rangle \in (OBJs)^n$, it must be the case that:

$$\text{if } p_1, p_2 \in f_{pfuns}(\pi, n)(o_1, o_2, \dots, o_n) \text{ and } p_1 \cup p_2 \in PERIODS, \text{ then } p_1 = p_2$$

This ensures that no two different periods p_1, p_2 in $f_{pfuns}(\pi, n)(o_1, \dots, o_n)$ overlap or are adjacent (because if they overlap or they are adjacent, then their union is also a period, and then it must be true that $p_1 = p_2$). Intuitively, if p_1 and p_2 overlap or are adjacent, we want $f_{pfuns}(\pi, n)(o_1, o_2, \dots, o_n)$ to contain their union $p_1 \cup p_2$ instead of p_1 and p_2 .

f_{culms}: f_{culms} is a function that maps each pair $\langle \pi, n \rangle$, where $\pi \in PFUNS$ and $n \in \{1, 2, 3, \dots\}$, to another function $(OBJs)^n \mapsto \{T, F\}$ (T, F are the two truth values). That is, for every $\pi \in PFUNS$ and each $n \in \{1, 2, 3, \dots\}$, $f_{culms}(\pi, n)$ is a function that maps each n -tuple of elements of $OBJs$ to T or F .

f_{culms} is only consulted in the case of predicates that represent actions or changes

that have inherent climaxes. If $\pi(\tau_1, \tau_2, \dots, \tau_n)$ represents such an action or change, and $\tau_1, \tau_2, \dots, \tau_n$ denote the world objects o_1, o_2, \dots, o_n , then $f_{pfuns}(\pi, n)(o_1, o_2, \dots, o_n)$ is the set of all maximal periods throughout which the action or change is ongoing. $f_{culms}(\pi, n)(o_1, o_2, \dots, o_n)$ shows whether or not the change or action reaches its climax at the latest time-point at which the change or action is ongoing. For example, if the constant j_adams denotes a person o_1 in the world, $bridge2$ denotes an object o_2 , and $building(j_adams, ba737)$ describes the situation whereby o_1 is building o_2 , $f_{pfuns}(building, 2)(o_1, o_2)$ will be the set of all maximal periods where o_1 is building o_2 . $f_{culms}(building, 2)(o_1, o_2)$ will be T if the building is completed at the end-point of the latest maximal period in $f_{pfuns}(building, 2)(o_1, o_2)$, and F otherwise. The role of f_{culms} will become clearer in section 3.9.

f_{gparts}: f_{gparts} is a function that maps each element of *GPARTS* to a *gappy partitioning*. A gappy partitioning is a subset S of *PERIODS*, such that for every $p_1, p_2 \in S$, $p_1 \cap p_2 = \emptyset$, and $\bigcup_{p \in S} p \neq PTS$. For example, $f_{gparts}(monday^g)$ could be the gappy partitioning of all Monday-periods.

f_{cparts}: f_{cparts} is a function that maps each element of *CPARTS* to a *complete partitioning*. A complete partitioning is a subset S of *PERIODS*, such that for every $p_1, p_2 \in S$, $p_1 \cap p_2 = \emptyset$, and $\bigcup_{p \in S} p = PTS$. For example, $f_{cparts}(day^c)$ could be the complete partitioning of all day-periods.

3.5 Variable assignment

A variable assignment with respect to (w.r.t.) a TOP model M is a function $g : VARS \mapsto OBJs$ (g assigns to each variable an element of *OBJs*). G_M , or simply G , is the set of all possible variable assignments w.r.t. M , i.e. G is the set of all functions $VARS \mapsto OBJs$.

If $g \in G$, $\beta \in VARS$, and $o \in OBJs$, then g_o^β is the variable assignment defined as follows: $g_o^\beta(\beta) = o$, and for every $\beta' \in VARS$ with $\beta' \neq \beta$, $g_o^\beta(\beta') = g(\beta')$.

3.6 Denotation of a TOP expression

Index of evaluation: An index of evaluation is an ordered 3-tuple $\langle st, et, lt \rangle$, such that $st \in PTS$, $et \in PERIODS$, and $lt \in PERIODS^*$.

st (*speech time*) is the time-point at which the English question is submitted to the NLITDB. et (*event time*) is a period where the situation described by a TOP expression takes place. lt (*localisation time*) can be thought of as a temporal window, within which et must be located. When computing the denotation of a TOP formula that corresponds to an English question, lt is initially set to PTS . That is, the temporal window covers the whole time-axis, and et is allowed to be located anywhere. Various operators, however, may narrow down lt , imposing constraints on where et can be placed.

Denotation w.r.t. M, st, et, lt, g : The denotation of a TOP expression ξ w.r.t. a model M , an index of evaluation $\langle st, et, lt \rangle$, and a variable assignment g , is written $\|\xi\|^{M, st, et, lt, g}$ or simply $\|\xi\|^{st, et, lt, g}$. When the denotation of ξ does not depend on st , et , and lt , I often write $\|\xi\|^{M, g}$ or simply $\|\xi\|^g$.

The denotations w.r.t. M, st, et, lt, g of TOP expressions are defined recursively, starting with the denotations of terms and atomic formulae which are defined below.

- If $\kappa \in CONS$, then $\|\kappa\|^g = f_{cons}(\kappa)$.
- If $\beta \in VARS$, then $\|\beta\|^g = g(\beta)$.
- If $\phi \in YNFORMS$, then $\|\phi\|^{st, et, lt, g} \in \{T, F\}$.

The general rule above means that in the case of yes/no formulae, we only need to define when the denotation is T . In all other cases the denotation is F .

- If $\phi_1, \phi_2 \in YNFORMS$, then $\|\phi_1 \wedge \phi_2\|^{st, et, lt, g} = T$ iff $\|\phi_1\|^{st, et, lt, g} = T$ and $\|\phi_2\|^{st, et, lt, g} = T$.
- If $\sigma \in PARTS$, $\beta \in VARS$, and $\nu_{ord} \in \{\dots, -3, -2, -1, 0\}$, then $\|Part[\sigma, \beta, \nu_{ord}]\|^g$ is T , iff all the following hold (below $f = f_{cparts}$ if $\sigma \in CPARTS$, and $f = f_{gparts}$ if $\sigma \in GPARTS$):

- $g(\beta) \in f(\sigma)$,
- if $\nu_{ord} = 0$, then $st \in g(\beta)$,
- if $\nu_{ord} \leq -1$, then the following set contains exactly $-\nu_{ord} - 1$ elements:

$$\{p \in f(\sigma) \mid \text{maxpt}(g(\beta)) \prec \text{minpt}(p) \text{ and } \text{maxpt}(p) \prec st\}$$

Intuitively, if $\nu_{ord} = 0$, then β must denote a period in the partitioning that contains st . If $\nu_{ord} \leq -1$, β must denote the $-\nu_{ord}$ -th period of the partitioning that is completely situated before the speech time (e.g. if $\nu_{ord} = -4$, β must denote the 4th period which is completely situated before st); that is, there must be $-\nu_{ord} - 1$ periods in the partitioning that fall completely between the end of the period denoted by β and st ($-(-4) - 1 = 3$ periods if $\nu_{ord} = -4$).

For example, if $f_{cparts}(day^c)$ is the partitioning of all day-periods, then $\|Part[day^c, \beta, 0]\|^g$ is T iff $g(\beta)$ covers exactly the whole current day. Similarly, $\|Part[day^c, \beta, -1]\|^g$ is T iff $g(\beta)$ covers exactly the whole previous day. ($Part[day^c, \beta, 0]$ and $Part[day^c, \beta, -1]$ can be used to represent the meanings of “today” and “yesterday”; see section 3.10.) The definition of $Part$ could be extended to allow positive values as its third argument. This would allow expressing “tomorrow”, “next January”, etc.

- If $\sigma \in PARTS$ and $\beta \in VARS$, then $\|Part[\sigma, \beta]\|^g = T$ iff $g(\beta) \in f(\sigma)$ (where $f = f_{cparts}$ if $\sigma \in CPARTS$, and $f = f_{gparts}$ if $\sigma \in GPARTS$).

$Part[\sigma, \beta]$ is a simplified version of $Part[\sigma, \beta, \nu_{ord}]$, used when we want to ensure that $g(\beta)$ is simply a period in the partitioning of σ .

- If $\pi \in PFUNS$ and $\tau_1, \tau_2, \dots, \tau_n \in TERMS$, then $\|\pi(\tau_1, \tau_2, \dots, \tau_n)\|^{st, et, lt, g}$ is T iff $et \sqsubseteq lt$ and for some $p_{mxl} \in f_{pfuns}(\pi, n)(\|\tau_1\|^g, \|\tau_2\|^g, \dots, \|\tau_n\|^g)$, $et \sqsubseteq p_{mxl}$.

Intuitively, for the denotation of a predicate to be T , et must fall within lt , and et must be a subperiod of a maximal period where the situation described by the predicate holds. It is trivial to prove that the definition above causes all TOP predicates to have the following property:

Homogeneity: A TOP formula ϕ is *homogeneous*, iff for every $st \in PTS$, $et \in PERIODS$, $lt \in PERIODS^*$, and $g \in G$, the following implication holds:¹

$$\text{if } et' \sqsubseteq et \text{ and } \|\phi\|^{st,et,lt,g} = T, \text{ then } \|\phi\|^{st,et',lt,g} = T$$

Intuitively, if a predicate is true at some et , then it is also true at any subperiod et' of et . Although TOP predicates are homogeneous, more complex formulae are not always homogeneous. Various versions of homogeneity have been used in [Allen 84], [Lascarides 88], [Richards *et al.* 89], [Kent 93], [Pratt & Bree 95], and elsewhere.

The denotation of a wh-formula w.r.t. st , et , lt , and g is defined below. It is assumed that $\beta_1, \beta_2, \beta_3, \dots, \beta_n \in VARS$ and $\phi \in YNFORMS$.

$$\bullet \|\beta_1 \beta_2 \dots \beta_n \phi\|^{st,et,lt,g} = \{\langle g(\beta_1), g(\beta_2), \dots, g(\beta_n) \rangle \mid \|\phi\|^{st,et,lt,g} = T\}$$

That is, if $\|\phi\|^{st,et,lt,g} = T$, then $\|\beta_1 \beta_2 \dots \beta_n \phi\|^{st,et,lt,g}$ is a one-element set; it contains one tuple that holds the world-objects assigned to $\beta_1, \beta_2, \dots, \beta_n$ by g . Otherwise, $\|\beta_1 \beta_2 \dots \beta_n \phi\|^{st,et,lt,g}$ is the empty set.

$$\begin{aligned} \bullet \|\beta_{mxl} \beta_1 \beta_2 \beta_3 \dots \beta_n \phi\|^{st,et,lt,g} = \\ \{\langle g(\beta_1), g(\beta_2), g(\beta_3), \dots, g(\beta_n) \rangle \mid \|\phi\|^{st,et,lt,g} = T, \text{ and} \\ \text{for no } et' \in PERIODS \text{ and } g' \in G \text{ is it true that } \|\phi\|^{st,et',lt,g'} = T, \\ g(\beta_1) \sqsubset g'(\beta_1), g(\beta_2) = g'(\beta_2), g(\beta_3) = g'(\beta_3), \dots, g(\beta_n) = g'(\beta_n)\} \end{aligned}$$

The denotation $\|\beta_{mxl} \beta_1 \beta_2 \beta_3 \dots \beta_n \phi\|^{st,et,lt,g}$ is either a one-element set that contains a tuple holding the world-objects $g(\beta_1), g(\beta_2), \dots, g(\beta_n)$, or the empty set. Intuitively, the denotation of $\beta_{mxl} \beta_1 \beta_2 \beta_3 \dots \beta_n \phi$ contains the values assigned to $\beta_1, \beta_2, \beta_3, \dots, \beta_n$ by g , if these values satisfy ϕ , and there is no other variable assignment g' that assigns the same values to $\beta_2, \beta_3, \dots, \beta_n$, a superperiod of $g(\beta_1)$ to β_1 , and that satisfies ϕ (for any $et' \in PERIODS$). That is, it must not be possible to extend any further the period assigned to β_1 by g , preserving at the same time the values assigned to $\beta_2, \beta_3, \dots, \beta_n$, and satisfying ϕ . Otherwise, the denotation of $\beta_{mxl} \beta_1 \beta_2 \beta_3 \dots \beta_n \phi$ is the empty set.

The syntax of TOP (section 3.2) requires β_1 to appear at least once within ϕ as the first argument of a *Past*, *Perf*, *At*, *Before*, *After*, or *Ntense* operator, or as the second

¹ The term “homogeneity” is also used in the temporal databases literature, but with a completely different meaning; see [Jensen *et al.* 93].

argument of a *Part* operator. The semantics of these operators require variables occurring at these positions to denote periods. Hence, variable assignments g that do not assign a period to β_1 will never satisfy ϕ , and no tuples for these variable assignments will be included in $\|\phi\|^{st,et,lt,g}$.

The rules for computing the denotations w.r.t. M, st, et, lt, g of other TOP expressions will be given in following sections.

Denotation w.r.t. M, st : I now define the denotation of a TOP expression with respect to only M and st . The denotation w.r.t. M, st is similar to the denotation w.r.t. M, st, et, lt, g , except that there is an implicit existential quantification over all $g \in G$ and all $et \in PERIODS$, and lt is set to PTS (the whole time-axis). The denotation of ϕ w.r.t. M, st , written $\|\phi\|^{M,st}$ or simply $\|\phi\|^{st}$, is defined only for TOP formulae:

- If $\phi \in YNFORMS$, then $\|\phi\|^{st} =$
 - T , if for some $g \in G$ and $et \in PERIODS$, $\|\phi\|^{st,et,PTS,g} = T$,
 - F , otherwise
- If $\phi \in WHFORMS$, then $\|\phi\|^{st} = \bigcup_{g \in G, et \in PERIODS} \|\phi\|^{st,et,PTS,g}$.

Each question will be mapped to a TOP formula ϕ (if the question is ambiguous, multiple formulae will be generated, one for each reading). $\|\phi\|^{st}$ specifies what the NLITDB's answer should report. When $\phi \in YNFORMS$, $\|\phi\|^{st} = T$ (i.e. the answer should be “yes”) if for some assignment to the variables of ϕ and for some event time, ϕ is satisfied; otherwise $\|\phi\|^{st} = F$ (the answer should be “no”). The localisation time is set to PTS (the whole time-axis) to reflect the fact that initially there is no restriction on where et may be located. As mentioned in section 3.6, however, when computing the denotations of the subformulae of ϕ , temporal operators may narrow down the localisation time, placing restrictions on et .

In the case where $\phi \in WHFORMS$ (i.e. $\phi = ?\beta_1 \dots ?\beta_n \phi'$ or $\phi = ?_{mxl}\beta_1 \dots ?\beta_n \phi'$ with $\phi' \in YNFORMS$), $\|\phi\|^{st}$ is the union of all $\|\phi\|^{st,et,PTS,g}$, for any $g \in G$ and $et \in PERIODS$. For each $g \in G$ and $et \in PERIODS$, $\|\phi\|^{st,et,PTS,g}$ is either an empty set or a one-element set containing a tuple that holds values of $\beta_1, \beta_2, \beta_3, \dots, \beta_n$ that satisfy ϕ' (β_1 must be maximal if $\phi \in WHFORMS_2$). Hence, $\|\phi\|^{st}$ (the union of all $\|\phi\|^{st,et,PTS,g}$) is the set of all tuples that hold values of $\beta_1, \beta_2, \beta_3, \dots, \beta_n$ that satisfy

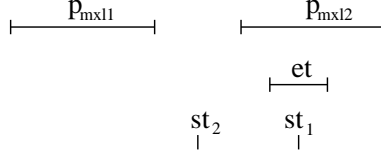


Figure 3.1: “Is BA737 at gate 2?”

ϕ' . The answer should report these tuples to the user (or be a message like “No answer found.”, if $\|\phi\|^{st} = \emptyset$).

3.7 The Pres operator

The *Pres* operator is used to express the simple present and present continuous tenses. For $\phi \in YNFORMS$:

- $\|Pres[\phi]\|^{st,et,lt,g} = T$, iff $st \in et$ and $\|\phi\|^{st,et,lt,g} = T$.

(3.3), for example, is represented as (3.4).

(3.3) Is BA737 at gate 2?

(3.4) $Pres[be_at(ba737, gate2)]$

Let us assume that the only maximal periods where BA737 was/is/will be at gate 2 are p_{mxl_1} and p_{mxl_2} (i.e. (3.5) holds; see section 3.4), and that (3.3) is submitted at a time-point st_1 , such that (3.6) holds (figure 3.1).

(3.5) $f_{pfuns}(be_at, 2)(f_{cons}(ba737), f_{cons}(gate2)) = \{p_{mxl_1}, p_{mxl_2}\}$

(3.6) $st_1 \in p_{mxl_2}$

The answer to (3.3) will be affirmative iff (3.7) is T .

(3.7) $\|Pres[be_at(ba737, gate2)]\|^{st_1}$

According to section 3.6, (3.7) is T iff for some $g \in G$ and $et \in PERIODS$, (3.8) holds.

(3.8) $\|Pres[be_at(ba737, gate2)]\|^{st_1, et, PTS, g} = T$

By the definition of *Pres*, (3.8) holds iff both (3.9) and (3.10) hold.

$$(3.9) \quad st_1 \in et$$

$$(3.10) \quad \|be_at(ba737, gate2)\|^{st_1, et, PTS, g} = T$$

By the definitions of $\|\pi(\tau_1, \dots, \tau_n)\|^{st, et, lt, g}$ and $\|\kappa\|^g$ (section 3.6), (3.10) holds iff for some p_{mxl} , (3.11) – (3.13) hold.

$$(3.11) \quad et \sqsubseteq PTS$$

$$(3.12) \quad p_{mxl} \in f_{pfun}(be_at, 2)(f_{cons}(ba737), f_{cons}(gate2))$$

$$(3.13) \quad et \sqsubseteq p_{mxl}$$

By (3.5), (3.12) is equivalent to (3.14).

$$(3.14) \quad p_{mxl} \in \{p_{mxl_1}, p_{mxl_2}\}$$

The answer to (3.3) will be affirmative iff for some $et \in PERIODS$ and some p_{mxl} , (3.9), (3.11), (3.13), and (3.14) hold. For $p_{mxl} = p_{mxl_2}$, and et any subperiod of p_{mxl_2} that contains st_1 (figure 3.1), (3.9), (3.11), (3.13), and (3.14) hold. Hence, the answer to (3.3) will be affirmative, as one would expect. If the question is submitted at an st_2 that falls outside p_{mxl_1} and p_{mxl_2} (figure 3.1), then the answer will be negative, because in that case there is no subperiod et of p_{mxl_1} or p_{mxl_2} that contains st_2 .

The present continuous is expressed similarly. For example, the reading of (3.15) where Airserve is actually servicing BA737 at the present moment is expressed as (3.16). Unlike [Dowty 77], [Lascarides 88], [Pirie *et al.* 90], and [Crouch & Pulman 93], in TOP progressive tenses do not introduce any special progressive operator. This will be discussed in section 3.9.

$$(3.15) \quad \text{Airserve is (actually) servicing BA737.}$$

$$(3.16) \quad Pres[servicing(airserve, ba737)]$$

The habitual (3.17) is represented using a different predicate functor from that of (3.15), as in (3.18). As will be explained in chapter 4, (3.15) is taken to involve a non-habitual homonym of “to service”, while (3.17) is taken to involve a habitual homonym. The two homonyms introduce different predicate functors.

$$(3.17) \quad \text{Airserve (habitually) services BA737.}$$

(3.18) $Pres[hab_server_of(airserve, ba737)]$

TOP's *Pres* operator is similar to that of [Pirie *et al.* 90]. The main difference is that the *Pres* of Pirie *et al.* does not require *st* to fall within *et*. Instead, it narrows *lt* to start at or after *st*. This, in combination with the requirement $et \sqsubseteq lt$, requires *et* to start at or after *st*. Using this version of *Pres* in (3.4) would cause the answer to be affirmative if (3.3) is submitted at st_2 (figure 3.1), i.e. at a point where BA737 is not at gate 2, because there is an *et* at which BA737 is at gate 2 (e.g. the *et* of figure 3.1), and this *et* starts after st_2 . This version of *Pres* was adopted by Pirie *et al.* to cope with sentences like “J.Adams inspects BA737 tomorrow.”, where the simple present refers to a future inspection (section 2.5.1). In this case, *et* (inspection time) must be allowed to start after *st*.

The *Pres* of Pirie *et al.* is often over-permissive (e.g. it causes the answer to be affirmative if (3.3) is submitted at st_2). Pirie *et al.* employ a post-processing mechanism, which is invoked after the English sentence is translated into logic, and which attempts to restrict the semantics of *Pres* in cases where it is over-permissive. In effect, this mechanism introduces modifications in only one case: if the *Pres* is introduced by a state verb (excluding progressive states) which is not modified by a temporal adverbial, then *et* is set to $\{st\}$. For example, in “J.Adams is at site 2.” where the verb is a state, the mechanism causes *et* to be set to $\{st\}$, which correctly requires J.Adams to be at gate 2 at *st*. In “J.Adams is at site 2 tomorrow.”, where the state verb is modified by a temporal adverbial, the post-processing has no effect, and *et* (the time where J.Adams is at site 2) is allowed to start at or after *st*. This is again correct, since in this case *et* must be located within the following day, i.e. after *st*. In “J.Adams is inspecting site 2.”, where the verb is a progressive state, the post-processing has again no effect, and *et* (inspection time) can start at or after *st*. The rationale in this case is that *et* cannot be set to $\{st\}$, because there is a reading where the present continuous refers to a future inspection (section 2.5.3). For the purposes of this project, where the futurate readings of the simple present and the present continuous are ignored, TOP's *Pres* is adequate. If, however, these futurate readings were to be supported, a more permissive *Pres* operator, like that of Pirie *et al.*, might have to be adopted.

3.8 The Past operator

The *Past* operator is used when expressing the simple past, the past continuous, the past perfect, and the present perfect (the latter is treated as equivalent to the simple past; section 2.5.4). For $\phi \in YNFORMS$ and $\beta \in VARS$:

- $\|Past[\beta, \phi]\|^{st, et, lt, g} = T$, iff $g(\beta) = et$ and $\|\phi\|^{st, et, lt \cap [t_{first}, st), g} = T$.

The *Past* operator narrows the localisation time, so that the latter ends before *st*. *et* will eventually be required to be a subperiod of the localisation time (this requirement will be introduced by the rules that compute the denotation of ϕ). Hence, *et* will be required to end before *st*. β is used as a pointer to *et* (the definition of $Past[\beta, \phi]$ makes sure that the value of β is *et*). β is useful in formulae that contain *Ntenses* (to be discussed in section 3.13). It is also useful in time-asking questions, where *et* has to be reported. For example, “When was gate 2 open?” is represented as $?_{maxl} e^v Past[e^v, open(gate2)]$, which reports the maximal *ets* that end before *st*, such that gate 2 is open throughout *et*.

TOP’s *Past* operator is essentially the same as that of [Pirie *et al.* 90]. (A slightly different *Past* operator is adopted in [Crouch & Pulman 93].)

3.9 Progressives, non-progressives, and the Culm operator

Let us now examine in more detail how TOP represents the simple past and the past continuous. Let us start from verbs whose base forms are culminating activities, like “to inspect” in the airport domain. The past continuous (3.19) is represented as (3.20).

(3.19) Was J.Adams inspecting BA737?

(3.20) $Past[e^v, inspecting(j_adams, ba737)]$

Let us assume that the inspection of BA737 by J.Adams started at the beginning of p_{maxl_1} (figure 3.2), that it stopped temporarily at the end of p_{maxl_1} , that it was resumed at the beginning of p_{maxl_2} , and that it was completed at the end of p_{maxl_2} . Let us also assume that there is no other time at which J.Adams was/is/will be inspecting BA737.

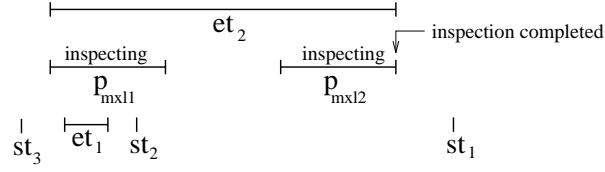


Figure 3.2: “Was J.Adams inspecting BA737?” vs. “Did J.Adams inspect BA737?”

Then, (3.21) and (3.22) hold.

(3.21)

$$f_{pfuns}(inspecting, 2)(f_{cons}(j_adams), f_{cons}(ba737)) = \{p_{mxl_1}, p_{mxl_2}\}$$

(3.22)

$$f_{culms}(inspecting, 2)(f_{cons}(j_adams), f_{cons}(ba737)) = T$$

The reader can check that (3.23) is T iff there is an et that is a subperiod of p_{mxl_1} or p_{mxl_2} , and that ends before st .

$$(3.23) \quad \|Past[e^v, inspecting(j_adams, ba737)]\|^{st}$$

If (3.19) is submitted at st_1 or st_2 (figure 3.2), then (3.23) is T (the answer to (3.19) will be “yes”), because in both cases there is an et (e.g. the et_1 of figure 3.2) that ends before st_1 and st_2 , and that is a subperiod of p_{mxl_1} . In contrast, if the question is submitted at st_3 , (3.23) is F (the answer will be negative), because in this case there is no subperiod of p_{mxl_1} or p_{mxl_2} that ends before st_3 . This is what one would expect: at st_1 and st_2 the answer to (3.19) should be affirmative, because J.Adams has already spent some time inspecting BA737. In contrast, at st_3 J.Adams has not yet spent any time inspecting BA737, and the answer should be negative.

Let us now consider the simple past (3.24). We want the answer to be affirmative if (3.24) is submitted at st_1 (or any other time-point after the end of p_{mxl_2}), but not if it is submitted at st_2 (or any other time-point before the end of p_{mxl_2}), because at st_2 J.Adams has not yet completed the inspection (section 2.5.2).

$$(3.24) \quad \text{Did J.Adams inspect BA737?}$$

(3.24) cannot be represented as (3.20), because this would cause the answer to (3.24) to be affirmative if the question is submitted at st_2 . Instead, (3.24) is represented as (3.25). The same predicate $inspecting(j_adams, ba737)$ of (3.20) is used, but an additional *Culm* operator is inserted.

$$(3.25) \quad Past[e^v, Culm[inspecting(j_adams, ba737)]]$$

Intuitively, the *Culm* requires the event time to be the et_2 of figure 3.2, i.e. to cover the whole time from the point where the inspection starts to the point where the inspection is completed. (If the inspection is never completed, *Culm* causes the denotation of (3.25) to be F .) Combined with the *Past* operator, the *Culm* causes the answer to be affirmative if (3.24) is submitted at st_1 (because et_2 ends before st_1), and negative if the question is submitted at st_2 (because et_2 does not end before st_2). More formally, for $\pi \in PFUNS$ and $\tau_1, \dots, \tau_n \in TERMS$:

- $\|Culm[\pi(\tau_1, \dots, \tau_n)]\|^{st, et, lt, g} = T$, iff $et \sqsubseteq lt$, $f_{culms}(\pi, n)(\|\tau_1\|^g, \dots, \|\tau_n\|^g) = T$, $S \neq \emptyset$, and $et = [\minpt(S), \maxpt(S)]$, where:

$$S = \bigcup_{p \in f_{pfuns}(\pi, n)(\|\tau_1\|^g, \dots, \|\tau_n\|^g)} p$$

The $et = [\minpt(S), \maxpt(S)]$ requires et to start at the first time-point where the change or action of $\pi(\tau_1, \dots, \tau_n)$ is ongoing, and to end at the latest time-point where the change or action is ongoing. The $f_{culms}(\pi)(\|\tau_1\|^g, \dots, \|\tau_n\|^g) = T$ means that the change or action must reach its climax at the latest time-point where it is ongoing.

Let us now check formally that the denotation (3.26) of (3.25) is in order.

$$(3.26) \quad \|Past[e^v, Culm[inspecting(j_adams, ba737)]]\|^{st}$$

(3.26) is T iff for some $g \in G$ and $et \in PERIODS$, (3.27) holds.

$$(3.27) \quad \|Past[e^v, Culm[inspecting(j_adams, ba737)]]\|^{st, et, PTS, g} = T$$

By the definition of *Past*, (3.27) holds iff (3.28) and (3.29) hold ($PTS \cap [t_{first}, st) = [t_{first}, st)$).

$$(3.28) \quad g(e^v) = et$$

$$(3.29) \quad \|Culm[inspecting(j_adams, ba737)]\|^{st, et, [t_{first}, st), g} = T$$

By the definition of *Culm*, (3.29) holds iff (3.30) – (3.34) hold.

$$(3.30) \quad et \sqsubseteq [t_{first}, st)$$

$$(3.31) \quad f_{culms}(inspecting, 2)(f_{cons}(j_adams), f_{cons}(ba737)) = T$$

$$(3.32) \quad S \neq \emptyset$$

$$(3.33) \quad et = [\minpt(S), \maxpt(S)]$$

$$(3.34) \quad S = \bigcup_{p \in f_{pfuns}(inspecting, 2)(f_{cons}(j_adams), f_{cons}(ba737))} p$$

By (3.21), and assuming that $\maxpt(p_{mxl_1}) \prec \minpt(p_{mxl_2})$ (as in figure 3.2), (3.32) – (3.34) are equivalent to (3.35) – (3.36). (3.35) holds (the union of two periods is never the empty set), and (3.31) is the same as (3.22), which was assumed to hold.

$$(3.35) \quad p_{mxl_1} \cup p_{mxl_2} \neq \emptyset$$

$$(3.36) \quad et = [\minpt(p_{mxl_1}), \maxpt(p_{mxl_2})]$$

Hence, (3.26) is T (i.e. the answer to (3.24) is affirmative) iff for some $g \in G$ and $et \in PTS$, (3.28), (3.30), and (3.36) hold. Let $et_2 = [\minpt(p_{mxl_1}), \maxpt(p_{mxl_2})]$ (as in figure 3.2).

Let us assume that (3.24) is submitted at an st that follows the end of et_2 (e.g. st_1 in figure 3.2). For $et = et_2$, (3.30) and (3.36) are satisfied. (3.28) is also satisfied by choosing $g = g_1$, where g_1 as below. Hence, the answer to (3.24) will be affirmative, as required.

$$g_1(\beta) = \begin{cases} et_2 & \text{if } \beta = e^v \\ o & \text{otherwise (} o \text{ is an arbitrary element of } OBJS \text{)} \end{cases}$$

In contrast, if the question is submitted before the end of et_2 (e.g. st_2 or st_3 in figure 3.2), then the answer to (3.24) will be negative, because there is no et that satisfies (3.30) and (3.36).

In the case of verbs whose base forms are processes, states, or points, the simple past does not introduce a *Culm* operator. In this case, when both the simple past and the past continuous are possible, they are represented using the same TOP formula. (A similar approach is adopted in [Parsons 89].) For example, in the airport domain where “to circle” is classified as process, both (3.37) and (3.38) are represented as (3.39).

$$(3.37) \quad \text{Was BA737 circling?}$$

$$(3.38) \quad \text{Did BA737 circle?}$$

$$(3.39) \quad \text{Past}[e^v, circling(ba737)]$$

The reader can check that the denotation of (3.39) w.r.t. st is T (i.e. the answer to (3.37) and (3.38) is affirmative) iff there is an et which is a subperiod of a maximal period where BA737 was circling, and et ends before st . That is, the answer is affirmative iff BA737 was circling at some time before st . There is no requirement that any climax must have been reached.

The reader will have noticed that in the case of verbs whose base forms are culminating activities, the (non-progressive) simple past is represented by adding a *Culm* operator to the expression that represents the (progressive) past continuous. For example, assuming that “to build (something)” is a culminating activity, (3.40) is represented as (3.41), and (3.42) as (3.43)).

(3.40) Housecorp was building bridge 2.

(3.41) $Past[e^v, building(housecorp, bridge2)]$

(3.42) Housecorp built bridge 2.

(3.43) $Past[e^v, Culm[building(housecorp, bridge2)]]$

In contrast, in [Dowty 77], [Lascarides 88], [Pirie *et al.* 90], [Crouch & Pulman 93], and [Kamp & Reyle 93], progressive tenses are represented by adding a progressive operator to the expressions that represent the non-progressive tenses. For example, ignoring some details, Pirie *et al.* represent (3.40) and (3.42) as (3.44) and (3.45) respectively.

(3.44) $Past[e^v, Prog[build(housecorp, bridge2)]]$

(3.45) $Past[e^v, build(housecorp, bridge2)]$

In (3.45), the semantics that Pirie *et al.* assign to $build(housecorp, bridge2)$ require *et* to cover the whole building of the bridge by Housecorp, from its beginning to the point where the building is complete. (The semantics of TOP’s $building(housecorp, bridge2)$ in (3.41) require *et* to be simply a period throughout which Housecorp is building bridge 2.) The *Past* of (3.45) requires *et* (start to completion of inspection) to end before *st*. Hence, the answer to (3.42) is affirmative iff the building was completed before *st*.

In (3.44), the semantics that Pirie *et al.* assign to *Prog* require *et* to be a subperiod of another period *et'* that covers the whole building (from start to completion; figure 3.3). The *Past* of (3.44) requires *et* to end before *st*. If, for example, (3.40) is submitted at an *st* that falls between the end of *et* and the end of *et'* (figure 3.3), the answer will be affirmative. This is correct, because at that *st* Housecorp has already been building the bridge for some time (although the bridge is not yet complete). The *Prog* of Pirie *et al.*, however, has a flaw (acknowledged in [Crouch & Pulman 93]): (3.44) implies that there is a period *et'*, such that the building is completed at the end of

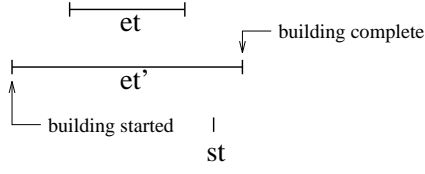


Figure 3.3: A flawed Prog operator

et' ; i.e. according to (3.44) the building was or will be necessarily completed at some time-point. This does not capture correctly the semantics of (3.40). (3.40) carries no implication that the building was or will ever be completed. (TOP's representation of (3.40), i.e. (3.41), does not suffer from this problem: it contains no assumption that the building is ever completed.) To overcome similar problems with *Prog* operators, “branching” models of time or “possible worlds” have been employed (see, for example, [Dowty 77], [McDermott 82], [Mays 86], [Kent 93]; see also [Lascarides 88] for criticism of possible-worlds approaches to progressives.) Approaches based on branching time and possible worlds, however, seem unnecessarily complicated for the purposes of this thesis.

3.10 The At, Before, and After operators

The *At*, *Before*, and *After* operators are used to express punctual adverbials, period adverbials, and “while ...”, “before ...”, and “after ...” subordinate clauses (sections 2.9 and 2.10). For $\phi, \phi_1, \phi_2 \in YNFORMS$ and $\tau \in TERMS$:

- $\|At[\tau, \phi]\|^{st, et, lt, g} = T$, iff $\|\tau\|^g \in PERIODS$ and $\|\phi\|^{st, et, lt \cap \|\tau\|^g, g} = T$.
- $\|At[\phi_1, \phi_2]\|^{st, et, lt, g} = T$, iff for some et'
 $et' \in \text{mxlpers}(\{\phi_1 \in PERIODS \mid \|\phi_1\|^{st, e, PTS, g} = T\})$ and $\|\phi_2\|^{st, et, lt \cap et', g} = T$.

If the first argument of *At* is a term τ , then τ must denote a period. The localisation time is narrowed to the intersection of the original *lt* with the period of τ . If the first argument of *At* is a formula ϕ_1 , the localisation time of ϕ_2 is narrowed to the intersection of the original *lt* with a maximal event time period et' at which ϕ_1 holds. For example, (3.46) is represented as (3.47).

(3.46) Was tank 2 empty (some time) on 25/9/95?

$$(3.47) \quad At[25/9/95, Past[e^v, empty(tank2)]]$$

In (3.47), lt initially covers the whole time-axis. The At operator causes lt to become the 25/9/95 period (I assume that the constant 25/9/95 denotes the obvious period), and the $Past$ operator narrows lt to end before st (if 25/9/95 is entirely in the past, the $Past$ operator has not effect). The answer to (3.46) is affirmative iff it is possible to find an et that is a subperiod of the narrowed lt , such that tank 2 was empty during et .

If (3.46) is submitted before 25/9/95 (i.e. 25/9/95 starts after st), the NLITDB's answer will be negative, because the At and $Past$ operators cause lt to become the empty set, and hence it is impossible to find a subperiod et of lt where tank 2 is empty. A simple negative response is unsatisfactory in this case: (3.46) is unacceptable if uttered before 25/9/95, and the system should warn the user about this. The unacceptability of (3.46) in this case seems related to the unacceptability of (3.48), which would be represented as (3.49) (the definition of $Part$ would have to be extended to allow positive values of its third argument; see section 3.6).

$$(3.48) \quad *Was \text{ tank 2 empty tomorrow?}$$

$$(3.49) \quad Part[day^c, tom^v, 1] \wedge At[tom^v, Past[e^v, empty(tank2)]]$$

In both cases, the combination of the simple past and the adverbial causes lt to become the empty set. In (3.48), tom^v denotes the period that covers exactly the day after st . The At and $Past$ operators set lt to the intersection of that period with $[t_{first}, st)$. The two periods do not overlap, and hence $lt = \emptyset$, and it is impossible to find a subperiod et of lt . This causes the answer to be always negative, no matter what happens in the world (i.e. regardless of when tank 2 is empty). Perhaps the questions sound unacceptable because people, using a concept similar to TOP's lt , realise that the answers can never be affirmative. This suggests that the NLITDB should check if $lt = \emptyset$, and if this is the case, generate a cooperative response (section 1.4) explaining that the question is problematic (this is similar to the “overlap rule” of [Harper & Charniak 86] and the “non-triviality constraint” on p. 653 of [Kamp & Reyle 93]). The framework of this thesis currently provides no such mechanism.

Moving to further examples, (3.50) and (3.53) are represented as (3.52) and (3.54). Unlike the “on 25/9/95” of (3.46), which is represented using a constant (25/9/95),

the “on Monday” of (3.50) is represented using a variable (mon^v) that ranges over the periods of the partitioning of Monday-periods. Similarly, the “at 5:00pm” of (3.53) is represented using a variable (fv^v) that ranges over the 5:00pm minute-periods.

- (3.50) Was tank 2 empty on Monday?
 (3.51) Was tank 2 empty on a Monday?
 (3.52) $Part[monday^g, mon^v] \wedge At[mon^v, Past[e^v, empty(tank2)]]$
 (3.53) Was tank 2 empty on Monday at 5:00pm?
 (3.54) $Part[monday^g, mon^v] \wedge Part[5:00pm^g, fv^v] \wedge$
 $At[mon^v, At[fv^v, Past[e^v, empty(tank2)]]]$

(3.52) requires tank 2 to have been empty at some past et that falls within some Monday. No attempt is made to determine exactly which Monday the user has in mind in (3.50) ((3.50) is treated as equivalent to (3.51); section 2.12). Similarly, (3.54) requires tank 2 to have been empty at some past et that falls within the intersection of some 5:00pm-period with some Monday-period.

Assuming that “to inspect” is a culminating activity (as in the airport application), the reading of (3.55) that requires the inspection to have both started and been completed within the previous day (section 2.9.2) is represented as (3.56). The *Culm* requires et to cover exactly the whole inspection, from its beginning to its completion. The *Past* requires et to end before st , and the *At* requires et to fall within the day before st .

- (3.55) Did J.Adams inspect BA737 yesterday?
 (3.56) $Part[day^c, y^v, -1] \wedge At[y^v, Past[e^v, Culm[inspecting(j_adams, ba737)]]]$

In contrast, (3.57) is represented as (3.58). In this case, et must be simply a subperiod of a maximal period where J.Adams was inspecting BA737, and also be located within the previous day.

- (3.57) Was J.Adams inspecting BA737 yesterday?
 (3.58) $Part[day^c, y^v, -1] \wedge At[y^v, Past[e^v, inspecting(j_adams, ba737)]]$

Finally, (3.59) is represented as (3.60), which intuitively requires BA737 to have been circling at some past period $e2^v$, that falls within some past maximal period $e1^v$ where gate 2 was open.

(3.59) Did BA737 circle while gate 2 was open?

(3.60) $At[Past[e1^v, open(gate2)], Past[e2^v, circling(ba737)]]$

The *Before* and *After* operators are similar. They are used to express adverbials and subordinate clauses introduced by “before” and “after”. For $\phi, \phi_1, \phi_2 \in YNFORMS$ and $\tau \in TERMS$:

- $\|Before[\tau, \phi]\|^{st, et, lt, g} = T$, iff $\|\tau\|^g \in PERIODS$ and $\|\phi\|^{st, et, lt \cap [t_{first}, minpt(\|\tau\|^g)], g} = T$.
- $\|Before[\phi_1, \phi_2]\|^{st, et, lt, g} = T$, iff for some et'
 $et' \in mxlpers(\{e \in PERIODS \mid \|\phi_1\|^{st, e, PTS, g} = T\})$, and
 $\|\phi_2\|^{st, et, lt \cap [t_{first}, minpt(et')], g} = T$.
- $\|After[\tau, \phi]\|^{st, et, lt, g} = T$, iff $\|\tau\|^g \in PERIODS$ and
 $\|\phi\|^{st, et, lt \cap (maxpt(\|\tau\|^g), t_{last}], g} = T$.
- $\|After[\phi_1, \phi_2]\|^{st, et, lt, g} = T$, iff for some et'
 $et' \in mxlpers(\{e \mid \|\phi_1\|^{st, e, PTS, g} = T\})$ and
 $\|\phi_2\|^{st, et, lt \cap (maxpt(et'), t_{last}], g} = T$.

If the first argument of *Before* is a term τ , τ must denote a period. The localisation time is required to end before the beginning of τ 's period. If the first argument of *Before* is a formula ϕ_1 , the localisation time of ϕ_2 is required to end before the beginning of a maximal event time period et' where ϕ_1 holds. The *After* operator is similar.

For example, (3.61) is expressed as (3.62), and the reading of (3.63) that requires BA737 to have departed after the *end* of a maximal period where the emergency system was in operation is expressed as (3.64). (I assume here that “to depart” is a point, as in the airport application.)

(3.61) Was tank 2 empty before 25/9/95?

(3.62) $Before[25/9/95, Past[e^v, empty(tank2)]]$

(3.63) BA737 departed after the emergency system was in operation.

(3.64) $After[Past[e1^v, in_operation(emerg_sys)], Past[e2^v, depart(ba737)]]$

(3.63) also has a reading where BA737 must have departed after the emergency system *started* to be in operation (section 2.10.2). To express this reading, we need the *Begin* operator of section 3.12 below.

TOP’s *At*, *Before*, and *After* operators are similar to those of [Pirie *et al.* 90]. The operators of Pirie *et al.*, however, do not narrow *lt* as in TOP. Instead, they place directly restrictions on *et*. For example, ignoring some details, the *After* $[\phi_1, \phi_2]$ of Pirie *et al.* requires ϕ_2 to hold at an event time et_2 that follows an et_1 where ϕ_1 holds (both et_1 and et_2 must fall within *lt*). Instead, TOP’s *After* $[\phi_1, \phi_2]$ requires et_1 to be a maximal period where ϕ_1 holds (et_1 does not need to fall within the original *lt*), and evaluates ϕ_2 with respect to a narrowed *lt*, which is the intersection of the original *lt* with et_1 . In most cases, both approaches lead to similar results. TOP’s approach, however, is advantageous in sentences like (3.65), where one may want to express the reading whereby the tank was empty *throughout* 26/9/95 (section 2.9.2).

(3.65) Tank 2 was empty on 26/9/95.

(3.66) $At[26/9/95, Past[e^v, empty(tank2)]]$

In these cases one wants *et* (time where the tank was empty) to cover all the available time, where by “available time” I mean the part of the time-axis where the tense and the adverbial allow *et* to be placed. This notion of “available time” is captured by TOP’s *lt*: the simple past and the “on 26/9/95” of (3.65) introduce *At* and *Past* operators that, assuming that (3.65) is submitted after 26/9/95, cause *lt* to become the period that covers exactly the day 26/9/95. The intended reading can be expressed easily in TOP by including an additional operator that forces *et* to cover the whole *lt* (this operator will be discussed in section 3.11). This method cannot be used in the language of Pirie *et al.* Their *Past* operator narrows the *lt* to the part of the time-axis up to *st*, but their *At* does not narrow *lt* any further; instead, it imposes a direct restriction on *et* (the semantics of Pirie *et al.*’s *At* is not very clear, but it seems that this restriction requires *et* to be a subperiod of 26/9/95). Hence, *lt* is left to be the time-axis up to *st*, and one cannot require *et* to cover the whole *lt*, because this would require the tank to be empty all the time from t_{first} to *st*.

The *At* operator of Pirie *et al.* also does not allow its first argument to be a formula, and it is unclear how they represent “while . . .” clauses. Finally, Pirie *et al.*’s *Before* allows counter-factual uses of “before” to be expressed (section 2.10.2). Counter-factuals are

not considered in this thesis, and hence Pirie et al.’s *Before* will not be discussed any further.

3.11 The Fills operator

As discussed in section 2.9.2, when states combine with period adverbials, there is often a reading where the situation of the verb holds *throughout* the adverbial’s period. For example, there is a reading of (3.67) where tank 2 was empty throughout 26/9/95, not at simply some part of that day.

(3.67) Tank 2 was empty on 26/9/95.

Similar behaviour was observed in cases where states combine with “*while ...*” subordinate clauses (section 2.10.1). For example, there is a reading of (3.68) whereby BA737 was at gate 2 throughout the entire inspection of UK160 by J.Adams, not at simply some time during the inspection.

(3.68) BA737 was at gate 2 while J.Adams was inspecting UK160.

It is also interesting that (3.69) cannot be understood as saying that tank 2 was empty throughout the period of “*last summer*”. There is, however, a reading of (3.69) where tank 2 was empty throughout the August of the previous summer.

(3.69) Tank 2 was empty in August last summer.

It seems that states give rise to readings where the situation of the verb covers the whole available localisation time. (3.70) – (3.72) would express the readings of (3.67) – (3.69) that are under discussion, if there were some way to force the event times of the predicates *empty(tank2)*, *be_at(ba737, gate2)*, and *empty(tank2)* to cover their whole localisation times.

(3.70) $At[26/9/95, Past[e^v, empty(tank2)]]$

(3.71) $At[Past[e1^v, inspecting(j_adams, uk160)], Past[e2^v, be_at(ba737, gate2)]]$

(3.72) $Part[August^g, aug^v] \wedge Part[summer^g, sum^v, -1] \wedge$
 $At[aug^v, At[sum^v, Past[e^v, empty(tank2)]]]$

The *Fills* operator achieves exactly this: it sets *et* to the whole of *lt*. For $\phi \in YNFORMS$:

- $\|Fills[\phi]\|^{st,et,lt,g} = T$, iff $et = lt$ and $\|\phi\|^{st,et,lt,g} = T$.

The readings of (3.67) – (3.69) that are under discussion can be expressed as (3.73) – (3.75) respectively.

$$(3.73) \quad At[26/9/95, Past[e^v, Fills[empty(tank2)]]]$$

$$(3.74) \quad At[Past[e1^v, inspecting(j_adams, uk160)], \\ Past[e2^v, Fills[be_at(ba737, gate2)]]]$$

$$(3.75) \quad Part[august^g, aug^v] \wedge Part[summer^g, sum^v, -1] \\ At[aug^v, At[sum^v, Past[e^v, Fills[empty(tank2)]]]]]$$

This suggests that when state expressions combine with period-specifying subordinate clauses or adverbials, the NLITDB could generate two formulae, one with and one without a *Fills*, to capture the readings where *et* covers the whole or just part of *lt*. As mentioned in section 2.9.2, this approach (which was tested in one version of the prototype NLITDB) has the disadvantage that it generates a formula for the reading where *et* covers the whole *lt* even in cases where this reading is impossible. In time-asking questions like (3.76), for example, the reading where *et* covers the whole *lt* (the whole 1994) is impossible, and hence the corresponding formula should not be generated.

$$(3.76) \quad \text{When was tank 5 empty in 1994?}$$

Devising an algorithm to decide when the formulae that contain *Fills* should or should not be generated is a task which I have not addressed. For simplicity, the prototype NLITDB and the rest of this thesis ignore the readings that require *et* to cover the whole *lt*, and hence the *Fills* operator is not used. The *Fills* operator, however, may prove useful to other researchers who may attempt to explore further the topic of this section.

3.12 The Begin and End operators

The *Begin* and *End* operators are used to refer to the time-points where a situation starts or ends. For $\phi \in YNFORMS$:

- $\|Begin[\phi]\|^{st,et,lt,g} = T$, iff $et \sqsubseteq lt$
 $et' \in mxlpers(\{e \in PERIODS \mid \|\phi\|^{st,e,PTS,g} = T\})$ and $et = \{minpt(et')\}$.

- $\|End[\phi]\|^{st,et,lt,g} = T$, iff $et \sqsubseteq lt$
 $et' \in mxlpers(\{e \in PERIODS \mid \|\phi\|^{st,e,PTS,g} = T\})$ and $et = \{maxpt(et')\}$.

$Begin[\phi]$ is true only at instantaneous event times et that are beginnings of maximal event times et' where ϕ holds. The End operator is similar.

The $Begin$ and End operators can be used to express “to start”, “to stop”, “to begin”, and “to finish” (section 2.6). For example, (3.77) is expressed as (3.78). Intuitively, in (3.78) the $Culm[inspecting(j_adams, uk160)]$ refers to an event-time period that covers exactly a complete inspection of UK160 by J.Adams (from start to completion). $End[Culm[inspecting(j_adams, uk160)]]$ refers to the end of that period, i.e. the completion point of J.Adams’ inspection. $Begin[inspecting(t_smith, ba737)]$ refers to the beginning of an inspection of BA737 by T.Smith. The beginning of T.Smith’s inspection must precede the completion point of J.Adams’ inspection, and both points must be in the past.

(3.77) Did T.Smith start to inspect BA737 before J.Adams finished inspecting UK160?

(3.78) $Before[Past[e1^v, End[Culm[inspecting(j_adams, uk160)]]],$
 $Past[e2^v, Begin[inspecting(t_smith, ba737)]]]$

The reading of (3.63) (section 3.10) that requires BA737 to have departed after the emergency system *started* to be in operation can be expressed as (3.79). (The reading of (3.63) where BA737 must have departed after the system *stopped* being in operation is expressed as (3.64).)

(3.79) $After[Past[e1^v, Begin[in_operation(emerg_sys)]]], Past[e2^v, depart(ba737)]]$

3.13 The Ntense operator

The framework of this thesis (section 2.11) allows noun phrases like “the sales manager” in (3.80) to refer either to the present (current sales manager) or the time of the verb tense (1991 sales manager). The *Ntense* operator is used to represent these two possible readings.

(3.80) What was the salary of the sales manager in 1991?

(3.81) $?slr^v Ntense[now^*, manager_of(mgr^v, sales)] \wedge$
 $At[1991, Past[e^v, salary_of(mgr^v, slr^v)]]]$

$$(3.82) \quad ?slr^v \text{ Ntense}[e^v, \text{manager_of}(mgr^v, \text{sales})] \wedge \\ \text{At}[1991, \text{Past}[e^v, \text{salary_of}(mgr^v, slr^v)]]$$

The reading of (3.80) where “the sales manager” refers to the present is represented as (3.81), while the reading where it refers to the time of the verb tense is represented as (3.82). Intuitively, (3.81) reports any slr^v , such that slr^v was the salary of mgr^v at some past time e^v that falls within 1991, and mgr^v is the manager of the sales department *at the present*. In contrast, (3.82) reports any slr^v , such that slr^v was the salary of mgr^v at some past time e^v that falls within 1991, and mgr^v was the manager of the sales department *at e^v* . Notice that in (3.82) the first argument of the *Ntense* is the same as the first argument of the *Past*, which is a pointer to the past event time where $\text{salary_of}(mgr^v, slr^v)$ is true (see the semantics of *Past* in section 3.8).

For $\phi \in \text{YNFORMS}$ and $\beta \in \text{VARS}$:

- $\| \text{Ntense}[\beta, \phi] \|^{st, et, lt, g} = T$, iff for some $et' \in \text{PERIODS}$, it is true that $g(\beta) = et'$ and $\| \phi \|^{st, et', PTS, g} = T$.
- $\| \text{Ntense}[\text{now}^*, \phi] \|^{st, et, lt, g} = T$, iff $\| \phi \|^{st, \{st\}, PTS, g} = T$.

Ntense evaluates ϕ with respect to a new event time et' , which may be different from the original event time et that is used to evaluate the part of the formula outside the *Ntense*. Within the *Ntense*, the localisation time is reset to *PTS* (whole time-axis) freeing et' from restrictions imposed on the original et . If the first argument of *Ntense* is now^* , the new event time is the instantaneous period that contains only st , i.e. the object to which the noun phrase refers must have at st the property described by ϕ . If the first argument of *Ntense* is a variable β , the new event time et' can generally be any period, and β denotes et' . In (3.82), however, β is the same as the first argument of the *Past*, which denotes the original et that the *Past* requires to be placed before st . This means that $\text{manager_of}(mgr^v, \text{sales})$ must hold at the same event time where $\text{salary_of}(mgr^v, slr^v)$ holds, i.e. the person mgr^v must be the sales manager at the same time where the salary of mgr^v is slr^v . If the first argument of the *Ntense* in (3.82) and the first argument of the *Past* were different variables, the answer would contain any 1991 salary of anybody who was, is, or will be the sales manager at any time. This would be useful in (3.83), where one may want to allow “Prime Minister” to refer to the Prime Ministers of all times, a reading that can be expressed as (3.84).

(3.83) Which Prime Ministers were born in Scotland?

(3.84) $?pm^v \text{ Ntense}[e1^v, p\text{minister}(pm^v)] \wedge \text{Past}[e2^v, \text{birth_in}(pm^v, \text{scotland})]$

The framework of this thesis, however, does not currently generate (3.84). (3.83) would receive only two formulae, one for current Prime Ministers, and one for persons that were Prime Ministers at the time they were born (the latter reading is, of course, unlikely).

Questions like (3.85) and (3.87), where temporal adjectives specify explicitly the times to which the noun phrases refer, can be represented as (3.86) and (3.88). (The framework of this thesis, however, does not support temporal adjectives other than “current”; see section 2.8.)

(3.85) What was the salary of the current sales manager in 1991?

(3.86) $?slr^v \text{ Ntense}[\text{now}^*, \text{manager_of}(mgr^v, \text{sales})] \wedge \text{At}[1991, \text{Past}[e^v, \text{salary_of}(mgr^v, slr^v)]]$

(3.87) What was the salary of the 1988 sales manager in 1991?

(3.88) $?slr^v \text{ Ntense}[e1^v, \text{At}[1988, \text{manager_of}(mgr^v, \text{sales})]] \wedge \text{At}[1991, \text{Past}[e^v, \text{salary_of}(mgr^v, slr^v)]]$

The *Ntense* operator of TOP is the same as the *Ntense* operator of [Crouch 91] and [Crouch & Pulman 93].

3.14 The For operator

The *For* operator is used to express “for . . . ” and duration “in . . . ” adverbials (sections 2.9.3 and 2.9.4). For $\sigma_c \in CPARTS$, $\nu_{qty} \in \{1, 2, 3, \dots\}$, and $\phi \in YNFORMS$:

- $\|For[\sigma_c, \nu_{qty}, \phi]\|^{st, et, lt, g} = T$, iff $\|\phi\|^{st, et, lt, g} = T$, and for some $p_1, p_2, \dots, p_{\nu_{qty}} \in f_{cparts}(\sigma_c)$, it is true that $\text{minpt}(p_1) = \text{minpt}(et)$, $\text{next}(\text{maxpt}(p_1)) = \text{minpt}(p_2)$, $\text{next}(\text{maxpt}(p_2)) = \text{minpt}(p_3)$, \dots , $\text{next}(\text{maxpt}(p_{\nu_{qty}-1})) = \text{minpt}(p_{\nu_{qty}})$, and $\text{maxpt}(p_{\nu_{qty}}) = \text{maxpt}(et)$.

$For[\sigma_c, \nu_{qty}, \phi]$ requires ϕ to be true at an event time period that is ν_{qty} σ_c -periods long. For example, assuming that month^c denotes the partitioning of month-periods (the period that covers exactly the August of 1995, the period for September of 1995, etc.), (3.89) can be expressed as (3.90).

(3.89) Was tank 2 empty for three months?

(3.90) $For[month^c, 3, Past[e^v, empty(tank2)]]$

(3.90) requires an event time et to exist, such that et covers exactly three continuous months, and tank 2 was empty throughout et . As noted in section 2.9.3, “for ...” adverbials are sometimes used to specify the duration of a *maximal* period where a situation holds, or to refer to the *total duration* of possibly non-overlapping periods where some situation holds. The current version of TOP cannot express such readings.

Expressions like “one week”, “three months”, “two years”, “two hours”, etc., are often used to specify a duration of seven days, 3×30 days, 2×365 days, 2×60 minutes, etc. (3.90) expresses (3.89) if “three months” refers to *calendar* months (e.g. from the beginning of a June to the end of the following August). If “three months” means 3×30 days, (3.91) has to be used instead. (I assume that day^c denotes the partitioning of day-periods: the period that covers exactly 26/9/95, the period for 27/9/95, etc.)

(3.91) $For[day^c, 90, Past[e^v, empty(tank2)]]$

Assuming that “to inspect” is a culminating activity (as in the airport application), (3.93) represents the reading of (3.92) where 42 minutes is the duration from the beginning of the inspection to the inspection’s completion (section 2.9.4). (3.93) requires et to cover the whole inspection (from beginning to completion), et to be in the past, and the duration of et to be 42 minutes.

(3.92) J.Adams inspected BA737 in 42 minutes.

(3.93) $For[minute^c, 42, Past[e^v, Culm[inspecting(j_adams, ba737)]]]$

Unlike (3.92), (3.94) does not require the inspection to have been completed (section 2.9.3). (3.94) is represented as (3.95), which contains no *Culm*. In this case, et must simply be a period throughout which J.Adams was inspecting BA737, it must be located in the past, and it must be 42 minutes long.

(3.94) J.Adams inspected BA737 for 42 minutes.

(3.95) $For[minute^c, 42, Past[e^v, inspecting(j_adams, ba737)]]$

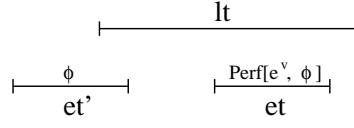


Figure 3.4: The Perf operator

3.15 The Perf operator

The *Perf* operator is used when expressing the past perfect. For example, (3.96) is expressed as (3.97). *Perf* could also be used to express the present perfect (e.g. (3.98) could be represented as (3.99)). This thesis, however, treats the present perfect in the same way as the simple past (section 2.5.4), and (3.98) is mapped to (3.101), the same formula that expresses (3.100).

(3.96) BA737 had departed.

(3.97) $Past[e1^v, Perf[e2^v, depart(ba737)]]$

(3.98) BA737 has departed.

(3.99) $Pres[Perf[e^v, depart(ba737)]]$

(3.100) BA737 departed.

(3.101) $Past[e^v, depart(ba737)]$

For $\phi \in YNFORMS$ and $\beta \in VARS$:

- $\|Perf[\beta, \phi]\|^{st, et, lt, g} = T$, iff $et \sqsubseteq lt$, and for some $et' \in PERIODS$, it is true that $g(\beta) = et'$, $maxpt(et') \prec minpt(et)$, and $\|\phi\|^{st, et', PTS, g} = T$.

$Perf[\beta, \phi]$ holds at the event time et , only if et is preceded by a new event time et' where ϕ holds (figure 3.4). The original et must be a subperiod of lt . In contrast et' does not need to be a subperiod of lt (the localisation time in $\|\phi\|^{st, et', PTS, g}$ is reset to PTS , the whole time-axis). The β of $Perf[\beta, \phi]$ is a pointer to et' , similar to the β of $Past[\beta, \phi]$. Ignoring constraints imposed by lt , the event time et where $Perf[\beta, \phi]$ is true can be placed anywhere within the period that starts immediately after the end of et' (et' is where ϕ is true) and that extends up to t_{last} . The informal term “consequent period” was used in section 2.9.1 to refer to this period.

Using the *Perf* operator, the reading of (3.102) where the inspection happens at some time before (or possibly on 27/9/95) is expressed as (3.103) (in this case, “on 27/9/95” provides a “reference time”; see section 2.5.5). In contrast, the reading of (3.102) where the inspection happens on 27/9/95 is expressed as (3.104).

(3.102) J.Adams had inspected gate 2 on 27/9/95.

(3.103) $At[27/9/95, Past[e1^v, Perf[e2^v, Culm[inspecting(ja, g2)]]]]$

(3.104) $Past[e1^v, Perf[e2^v, At[27/9/95, Culm[inspecting(ja, g2)]]]]$

Let us explore formally the denotations of (3.103) and (3.104). The denotation of (3.103) w.r.t. *st* is *T* iff for some *et* $\in PERIODS$ and *g* $\in G$, (3.105) holds.

(3.105) $\|At[27/9/95, Past[e1^v, Perf[e2^v, Culm[inspecting(ja, g2)]]]\|^{st, et, PTS, g} = T$

Assuming that 27/9/95 denotes the obvious period, by the definition of *At*, (3.105) holds iff (3.106) is true ($PTS \cap f_{cons}(27/9/95) = f_{cons}(27/9/95)$).

(3.106) $\|Past[e1^v, Perf[e2^v, Culm[inspecting(ja, g2)]]\|^{st, et, f_{cons}(27/9/95), g} = T$

By the definition of *Past*, ignoring *e1^v* which does not play any interesting role here, and assuming that *st* follows 27/9/95, (3.106) is true iff (3.107) holds.

(3.107) $\|Perf[e2^v, Culm[inspecting(ja, g2)]]\|^{st, et, f_{cons}(27/9/95), g} = T$

By the definition of *Perf* (ignoring *e2^v*), (3.107) holds iff for some *et'* $\in PERIODS$, (3.108), (3.109), and (3.110) hold.

(3.108) $et \sqsubseteq f_{cons}(27/9/95)$

(3.109) $maxpt(et') \prec minpt(et)$

(3.110) $\|Culm[inspecting(ja, g2)]\|^{st, et', PTS, g} = T$

By the definition of *Culm*, (3.110) holds iff (3.111) – (3.115) hold.

(3.111) $et' \sqsubseteq PTS$

(3.112) $f_{culms}(inspecting, 2)(f_{cons}(ja), f_{cons}(g2)) = T$

(3.113)
$$S = \bigcup_{p \in f_{pfuns}(inspecting, 2)(f_{cons}(ja), f_{cons}(g2))} p$$

(3.114) $S \neq \emptyset$

(3.115) $et' = [minpt(S), maxpt(S)]$

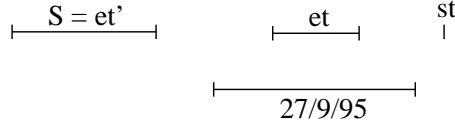


Figure 3.5: First reading of “J.Adams had inspected gate 2 on 27/9/95”

Let us assume that there is only one maximal period where J.Adams is inspecting BA737, and that the inspection is completed at the end of that period. Then, the S of (3.113) is the maximal period, and (3.112) and (3.114) hold. (3.115) requires et' to be the same period as S , in which case (3.111) is trivially satisfied. The denotation of (3.103) w.r.t. st is T (i.e. the answer to (3.102) is affirmative) iff for some et , $et' = S$, and (3.108) and (3.109) hold, i.e. iff there is an et within 27/9/95, such that et follows S ($S = et'$ is the period that covers the whole inspection). The situation is depicted in figure 3.5. In other words, 27/9/95 must contain an et where the inspection has already been completed.

Let us now consider (3.104). Its denotation w.r.t. st will be true iff for some $et \in PERIODS$ and $g \in G$, (3.116) holds.

$$(3.116) \quad \|Past[e1^v, Perf[e2^v, At[27/9/95, Culm[inspecting(ja, g2)]]]]\|^{st, et, PTS, g} = T$$

By the definition of $Past$, (3.116) holds iff (3.117) is true. (For simplicity, I ignore again $e1^v$ and $e2^v$.)

$$(3.117) \quad \|Perf[e2^v, At[27/9/95, Culm[inspecting(ja, g2)]]]\|^{st, et, [t_{first}, st), g}$$

By the definition of $Perf$, (3.117) is true iff for some $et' \in PERIODS$, (3.118), (3.119), and (3.120) hold.

$$(3.118) \quad et \sqsubseteq [t_{first}, st)$$

$$(3.119) \quad maxpt(et') \prec minpt(et)$$

$$(3.120) \quad \|At[27/9/95, Culm[inspecting(ja, g2)]]\|^{st, et', PTS, g} = T$$

By the definition of the At operator, (3.120) holds iff (3.121) holds. (I assume again that 27/9/95 denotes the obvious period.)

$$(3.121) \quad \|Culm[inspecting(ja, g2)]\|^{st, et', f_{cons}(27/9/95), g} = T$$

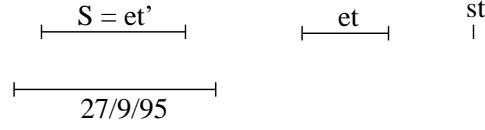


Figure 3.6: Second reading of “J.Adams had inspected gate 2 on 27/9/95”

By the definition of $Culm$, (3.121) holds iff (3.122) – (3.126) are true.

$$(3.122) \quad et' \sqsubseteq f_{cons}(27/9/95)$$

$$(3.123) \quad f_{culms}(inspecting, 2)(f_{cons}(ja), f_{cons}(g2)) = T$$

$$(3.124) \quad S = \bigcup_{p \in f_{pfuns}(inspecting, 2)(f_{cons}(ja), f_{cons}(g2))} p$$

$$(3.125) \quad S \neq \emptyset$$

$$(3.126) \quad et' = [minpt(S), maxpt(S)]$$

Assuming again that there is only one maximal period where J.Adams is inspecting BA737, and that the inspection is completed at the end of that period, the S of (3.124) is the maximal period, and (3.123) and (3.125) hold. (3.126) requires et' to be the same as S . The denotation of (3.104) w.r.t. st is T (i.e. the answer to (3.102) is affirmative) iff for some et , $et' = S$, and (3.118), (3.119), and (3.122) hold. That is there must be some past et that follows S ($S = et'$ is the period that covers the whole inspection), with S falling within 27/9/95 (figure 3.5). The inspection must have been completed within 27/9/95.

In (3.127), where there are no temporal adverbials, the corresponding formula (3.128) requires some past et (pointed to by $e1^v$) to exist, such that et follows an et' (pointed to by $e2^v$) that covers exactly the whole (from start to completion) inspection of gate 2 by J.Adams. The net effect is that the inspection must have been completed in the past.

$$(3.127) \quad \text{J.Adams had inspected gate 2}$$

$$(3.128) \quad Past[e1^v, Perf[e2^v, Culm[inspecting(ja, g2)]]]$$

As noted in section 2.5.5, there is a reading of (3.129) (probably the preferred one) whereby the two-year period ends on 1/1/94, i.e. J.Adams was still a manager on 1/1/94. Similarly, there is a reading of (3.130), whereby the two-year period ends at

st, i.e. J.Adams is still a manager (section 2.5.4). These readings cannot be captured in TOP.

(3.129) On 1/1/94, J.Adams had been a manager for two years.

(3.130) J.Adams has been a manager for two years.

For example, (3.131) requires some past *et* (pointed to by $e1^v$) to exist, such that *et* falls within 1/1/94, *et* follows a period *et'* (pointed to by $e2^v$), *et'* is a period where J.Adams is a manager, and the duration of *et'* is two years. If, for example, J.Adams was a manager only from 1/1/88 to 31/12/89, (3.131) causes the answer to (3.129) to be affirmative. (3.131) does not require the two-year period to end on 1/1/94.

(3.131) $At[1/1/94, Past[e1^v, Perf[e2^v, For[year^c, 2, be(ja, manager)]]]]$

Various versions of *Perf* operators have been used in [Dowty 82], [Richards *et al.* 89], [Pirie *et al.* 90], [Crouch & Pulman 93], and elsewhere.

3.16 Occurrence identifiers

Predicates introduced by verbs whose base forms are culminating activities often have an extra argument that acts as an *occurrence identifier*. Let us consider a scenario involving an engineer, John, who worked on engine 2 repairing faults of the engine at several past times (figure 3.7). John started repairing a fault of engine 2 on 1/6/92 at 9:00am. He continued to work on this fault up to 1:00pm on the same day, at which point he temporarily abandoned the repair without completing it. He resumed the repair at 3:00pm on 25/6/92, and completed it at 5:00pm on the same day.

In 1993, John was asked to repair another fault of engine 2. He started the repair on 1/7/93 at 9:00am, and continued to work on that fault up to 1:00pm on the same day without completing the repair. He then abandoned the repair for ever (John was not qualified to fix that fault, and the repair was assigned to another engineer). Finally, in 1994 John was asked to repair a third fault of engine 2. He started to repair the third fault on 1/6/94 at 9:00am, and continued to work on that fault up to 1:00pm on the same day, without completing the repair. He resumed the repair at 3:00pm, and completed it at 5:00pm on the same day.

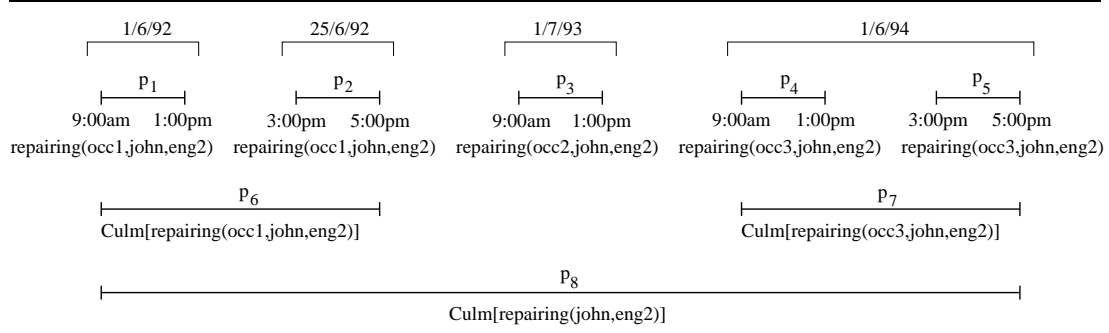


Figure 3.7: Occurrence identifiers

There is a problem if (3.132) is represented as (3.133). Let us assume that the question is submitted after 1/6/94. One would expect the answer to be affirmative, since a complete past repair of engine 2 by John is situated within 1/6/94. In contrast, (3.133) causes the answer to be negative. The semantics of *Culm* (section 3.9) requires *et* to start at the beginning of the earliest maximal period where *repairing(john,eng2)* holds (i.e. at the beginning of p_1 in figure 3.7) and to end at the end of the latest maximal period where *repairing(john,eng2)* holds (i.e. at the end of p_5 in figure 3.7). That is, *et* must be p_8 of figure 3.7. The *At* requires *et* (p_8) to be also a subperiod of 1/6/94. Since this is not the case, the answer is negative.

(3.132) Did John repair engine 2 on 1/6/94?

(3.133) $At[1/6/94, Past[e^v, Culm[repairing(john,eng2)]]]$

The problem is that although John was repairing engine 2 during all five periods (p_1 , p_2 , p_3 , p_4 , and p_5), the five periods intuitively belong to different occurrences of the situation where John is repairing engine 2. The first two periods have to do with the repair of the first fault (occurrence 1), the third period has to do with the repair of the second fault (occurrence 2), and the last two periods relate to the repair of the third fault (occurrence 3). The $Culm[repairing(john,eng2)]$ of (3.133), however, does not distinguish between the three occurrences, and forces *et* to start at the beginning of p_1 and to end at the end of p_5 . Instead, we would like $Culm[repairing(john,eng2)]$ to distinguish between the three occurrences: to require *et* to start at the beginning of p_1 (beginning of the first repair) and to end at the end of p_2 (completion of the first repair), or to require *et* to start at the beginning of p_4 (beginning of the third repair) and to end at the end of p_5 (completion of the third repair). ($Culm[repairing(john,eng2)]$)

should not allow et to be p_3 , because the second repair does not reach its completion at the end of p_3 .)

To achieve this, an occurrence-identifying argument is added to $fixing(john, eng2)$. If $occ1$, $occ2$, and $occ3$ denote the three repairing-occurrences, $fixing(occ1, john, eng2)$ will be true only at ets that are subperiods of p_1 or p_2 , $fixing(occ2, john, eng2)$ only at ets that are subperiods of p_3 , and $fixing(occ3, john, eng2)$ only at ets that are subperiods of p_4 or p_5 . In practice, the occurrence-identifying argument is always a variable. For example, (3.132) is now represented as (3.134) instead of (3.133).

$$(3.134) \quad At[1/6/94, Past[e^v, Culm[repairing(occ^v, john, eng2)]]]$$

Intuitively, according to (3.134) the answer should be affirmative if there is an et and a particular occurrence occ^v of the situation where John is repairing engine 2, such that et starts at the beginning of the first period where occ^v is ongoing, et ends at the end of the last period where occ^v is ongoing, occ^v reaches its completion at the end of et , and et falls within the past and 1/6/94. Now if (3.132) is submitted after 1/6/94, the answer is affirmative.

To see that (3.134) generates the correct result, let us examine the denotation of (3.134). The denotation of (3.134) w.r.t. st is affirmative if for some $et \in PERIODS$ and $g \in G$, (3.135) holds.

$$(3.135) \quad \|At[1/6/94, Past[e^v, Culm[repairing(occ^v, john, eng2)]]]\|^{st, et, PTS, g} = T$$

Assuming that the question is submitted after 1/6/94, and that 1/6/94 denotes the obvious period, by the definitions of At and $Past$, (3.135) holds iff (3.136) and (3.137) hold.

$$(3.136) \quad g(e^v) = et$$

$$(3.137) \quad \|Culm[repairing(occ^v, john, eng2)]\|^{st, et, fcons(1/6/94), g} = T$$

By the definition of $Culm$, (3.137) holds iff (3.138) – (3.141) hold, where S is as in

(3.142).

$$(3.138) \quad et \sqsubseteq f_{cons}(1/6/94)$$

$$(3.139) \quad f_{culms}(repairing, 2)(g(occ^v), f_{cons}(john), f_{cons}(eng2)) = T$$

$$(3.140) \quad S \neq \emptyset$$

$$(3.141) \quad et = [minpt(S), maxpt(S)]$$

$$(3.142) \quad S = \bigcup_{p \in f_{pfun}(repairing, 2)(g(occ^v), f_{cons}(john), f_{cons}(eng2))} p$$

The denotation of (3.134) w.r.t. st is T (i.e. the answer to (3.132) is affirmative), iff for some $et \in PERIODS$ and $g \in G$, (3.136) and (3.138) – (3.141) hold. For et as in (3.143) and g the variable assignment of (3.144), (3.136) and (3.138) hold. (3.142) becomes (3.145), and (3.140) holds. (3.141) becomes (3.143), which holds (et was chosen to satisfy it). (3.139) also holds, because the third repair is completed at the end of p_5 .

$$(3.143) \quad et = [minpt(p_4), maxpt(p_5)] = p_7$$

(3.144)

$$g(\beta) = \begin{cases} et & \text{if } \beta = e^v \\ f_{cons}(occ3) & \text{if } \beta = occ^v \\ o & \text{otherwise (} o \text{ is an arbitrary element of } OBJS \text{)} \end{cases}$$

$$(3.145) \quad S = p_4 \cup p_5$$

Hence, there is some $et \in PERIODS$ and $g \in G$ for which (3.136) and (3.138) – (3.141) hold, i.e. the answer to (3.132) will be affirmative as wanted.

Occurrence identifiers are a step towards formalisms that treat occurrences of situations (or “events” or “episodes”) as objects in the modelled world (e.g. [Parsons 90], [Kamp & Reyle 93], [Blackburn *et al.* 94], [Hwang & Schubert 94]). In TOP all terms (constants and variables) denote elements of *OBJs*, i.e. objects of the modelled world. Thus, allowing occurrence-identifying terms (like occ^v in (3.134)) implies that occurrences of situations are also world objects. Unlike other formalisms (e.g. those mentioned above), however, TOP does not treat these occurrence-identifying terms in any special way, and there is nothing in the definition of TOP to distinguish objects denoted by occurrence-identifiers from objects denoted by other terms.

3.17 Tense anaphora and localisation time

Although tense anaphora (section 2.12) was not considered during the work of this thesis, it seems that TOP's localisation time could prove useful if this phenomenon were to be supported. As noted in section 2.12, some cases of tense anaphora can be handled by storing the temporal window established by adverbials and tenses of previous questions, and by requiring the situations of follow-up questions to fall within that window. TOP's *lt* can capture this notion of previous window. Assuming that (3.146) is submitted after 1993, the *At* and *Past* operators of the corresponding formula (3.147) narrow *lt* to the period that covers exactly 1993. This period could be stored, and used as the initial value of *lt* in (3.149), that expresses the follow-up question (3.148). In effect, (3.148) would be taken to mean (3.150).

(3.146) Was Mary the personnel manager in 1993?

(3.147) $At[1993, Past[e^v, manager_of(mary, personnel)]]$

(3.148) Who was the personnel manager?

(3.149) $?wh^v Past[e^v, manager_of(wh^v, personnel)]$

(3.150) Who was the personnel manager in 1993?

Substantial improvements are needed to make these ideas workable. For example, if (3.146) and (3.148) are followed by (3.151) (expressed as (3.152)), and the dialogue takes place after 1993, the NLITDB must be intelligent enough to reset *lt* to the whole time axis. Otherwise, no person will ever be reported, because the *Pres* of (3.152) requires *et* to contain *st*, and an *et* that contains *st* can never fall within the past year 1993 (the *lt* of the previous question).

(3.151) Who is (now) the personnel manager?

(3.152) $?wh^v Pres[manager_of(wh^v, personnel)]$

3.18 Expressing habituals

As noted in section 3.7, habitual readings of sentences are taken to involve habitual homonyms of verbs. Habitual homonyms introduce different predicates than the corresponding non-habitual ones. For example, (3.153) and (3.155) would be expressed as (3.154) and (3.156) respectively. Different predicates would be used in the two cases.

(3.153) Last month BA737 (habitually) departed from gate 2.

(3.154) $Part[month^c, mon^v, -1] \wedge$
 $At[mon^v, Past[e^v, hab_depart_from(ba737, gate2)]]$

(3.155) Yesterday BA737 (actually) departed from gate 2.

(3.156) $Part[day^c, y^v, -1] \wedge$
 $At[y^v, Past[e^v, actl_depart_from(ba737, gate2)]]$

$hab_depart_from(ba737, gate2)$ is intended to hold at *ets* that fall within periods where BA737 has the habit of departing from gate 2. If BA737 departed habitually from gate 2 throughout 1994, $hab_depart_from(ba737, gate2)$ would be true at any *et* that is a subperiod of 1994. In contrast, $actl_depart_from(ba737, gate2)$ is intended to hold only at *ets* where BA737 actually departs from gate 2. If departures are modelled as instantaneous (as in the airport application), $actl_depart_from(ba737, gate2)$ is true only at instantaneous *ets* where BA737 leaves gate 2. One would expect that if BA737 had the habit of departing from gate 2 during some period, it would also have actually departed from gate 2 at least some times during that period: if $hab_depart_from(ba737, gate2)$ is true at an *et*, $actl_depart_from(ba737, gate2)$ would also be true at some subperiods *et'* of *et*. There is nothing in the definition of TOP, however, to guarantee that this implication holds. The event times where $hab_depart_from(ba737, gate2)$ and $actl_depart_from(ba737, gate2)$ hold are ultimately determined by f_{pfuns} (that specifies the maximal periods where the two predicates hold; see section 3.4). There is no restriction in the definition of TOP to prohibit whoever defines f_{pfuns} from specifying that $hab_depart_from(ba737, gate2)$ is true at some *et* that does not contain any *et'* where $actl_depart_from(ba737, gate2)$ is true.

Another issue is how to represent (3.157). (3.157) cannot be represented as (3.158).

(3.158) says that at 5:00pm on some day in the previous month BA737 had the habit of departing. I have found no elegant solution to this problem. (3.157) is mapped to (3.159), where the constant *5:00pm* is intended to denote a generic representative of 5:00pm-periods. This generic representative is taken to be an entity in the world.

(3.157) Last month BA737 (habitually) departed at 5:00pm.

(3.158) $Part[month^c, mon^v, -1] \wedge Part[5:00pm^g, fv^v] \wedge$
 $At[mon^v, At[fv^v, Past[e^v, hab_depart(ba737)]]$

(3.159) $Part[month^c, mon^v, -1] \wedge$
 $At[mon^v, Past[e^v, hab_depart_time(ba737, 5:00pm)]]$

Unlike (3.157), where “at 5:00pm” introduces a constant (*5:00pm*) as a predicate-argument in (3.159), the “at 5:00pm” of (3.160) introduces an *At* operator in (3.161).

(3.160) Yesterday BA737 (actually) departed at 5:00pm.

(3.161) $Part[day^c, y^v, -1] \wedge Part[5:00pm^g, fv^v] \wedge$
 $At[y^v, At[fv^v, Past[e^v, actl_depart(ba737)]]]$

The fact that “at 5:00pm” is treated in such different ways in the two cases is admittedly counter-intuitive, and it also complicates the translation from English to TOP (to be discussed in chapter 4).

3.19 Summary

TOP is a formal language, used to represent the meanings of the English questions that are submitted to the NLITDB. The denotation with respect to *st* of a TOP formula specifies what the answer to the corresponding English question should report (*st* is the time-point where the question is submitted to the NLITDB). The denotations with respect to *st* of TOP formulae are defined in terms of the denotations of TOP formulae with respect to *st*, *et*, and *lt*. *et* (event time) is a time period where the situation described by the formula holds, and *lt* (localisation time) is a temporal window within which *et* must be placed.

Temporal linguistic mechanisms are expressed in TOP using temporal operators that manipulate *st*, *et*, and *lt*. There are thirteen operators in total. *Part* picks a period from a partitioning. *Pres* and *Past* are used when expressing present and past tenses. *Perf* is used in combination with *Past* to express the past perfect. *Culm* is used to represent non-progressive forms of verbs whose base forms are culminating activities. *At*, *Before*, and *After* are employed when expressing punctual and period adverbials, and when expressing “while ...”, “before ...”, and “after ...” subordinate clauses. Duration “in ...” and “for ...” adverbials are expressed using *For*. *Fills* can be used to represent readings of sentences where the situation of the verb covers the whole localisation time; *Fills*, however, is not used in the rest of this thesis, nor in the prototype NLITDB. *Begin* and *End* are used to refer to time-points where situations start or stop. Finally, *Ntense* allows noun phrases to refer either to *st* or to the time of the verb’s tense.

Chapter 4

From English to TOP

“One step at a time.”

4.1 Introduction

This chapter shows how HPSG [Pollard & Sag 87] [Pollard & Sag 94] was modified to map English questions directed to a NLITDB to appropriate TOP formulae.¹ Although several modifications to HPSG were introduced, the HPSG version of this thesis remains very close to [Pollard & Sag 94]. The main differences from [Pollard & Sag 94] are that: (a) HPSG mechanisms for phenomena not examined in this thesis (e.g. pronouns, relative clauses) were removed, and (b) the situation-theoretic semantic constructs of HPSG were replaced by feature structures that represent TOP expressions.

Readers with a rudimentary grasp of modern unification-based grammars [Shieber 86] should be able to follow most of the discussion in this chapter. Some of the details, however, may be unclear to readers not familiar with HPSG. The HPSG version of this thesis was implemented as a grammar for the ALE system (see chapter 6).

4.2 HPSG basics

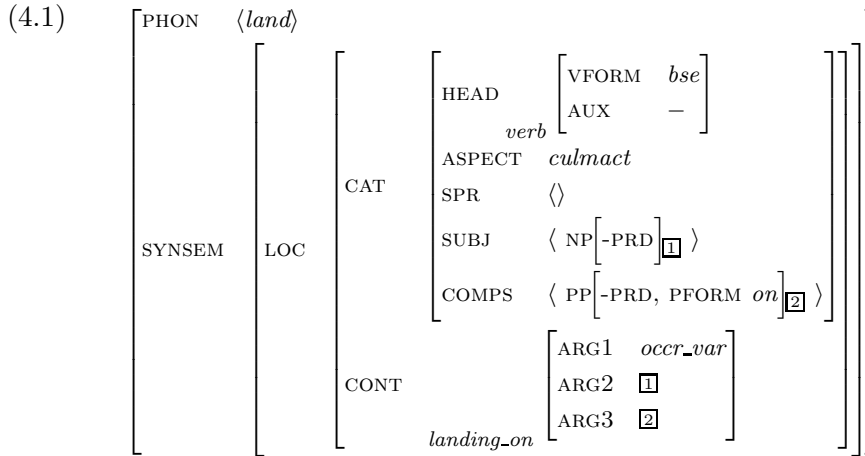
In HPSG, each word and syntactic constituent is mapped to a *sign*, a feature structure of a particular form, that provides information about the word or syntactic constituent. An HPSG grammar consists of signs for words (I call these *lexical signs*), *lexical rules*,

¹ The HPSG version of this thesis is based on the revised HPSG version of chapter 9 of [Pollard & Sag 94].

schemata, principles, and a sort hierarchy, all discussed below.

4.2.1 Lexical signs and sort hierarchy

Lexical signs provide information about individual words. (Words with multiple uses may receive more than one lexical sign.) (4.1) shows a lexical sign for the base form of “to land” in the airport domain.



The \langle and \rangle delimiters denote lists. The PHON feature shows the list of words to which the sign corresponds ((4.1) corresponds to the single word “land”). Apart from PHON, every sign has a SYNSEM feature (as well as other features not shown in (4.1); I often omit features that are not relevant to the discussion). The value of SYNSEM in (4.1) is a feature structure that has a feature LOC. The value of LOC is in turn a feature structure that has the features CAT (intuitively, syntactic category) and CONT (intuitively, semantic content).

Each HPSG feature structure belongs to a particular sort. The sort hierarchy of HPSG shows the available sorts, as well as which sort is a subsort of which other sort. It also specifies which features the members of each sort must have, and the sorts to which the values of these features must belong. (Some modifications were made to the sort hierarchy of [Pollard & Sag 94]. These will be discussed in sections 4.3 and 4.4.) In (4.1), for example, the value of HEAD is a feature structure of sort *verb*. The value of HEAD signals that the word is the base form (VFORM *bse*) of a non-auxiliary (AUX $-$) verb. The sort hierarchy of [Pollard & Sag 94] specifies that the value of HEAD must be of sort *head*, and that *verb* is a subsort of *head*. This allows feature structures of sort *verb* to be used as values of HEAD. The value of VFORM in (4.1) is an *atomic*

feature structure (a feature structure of no features) of sort *bse*. For simplicity, when showing feature structures I often omit uninteresting sort names.

ASPECT is the only new HPSG feature of this thesis. It is a feature of feature structures of sort *cat* (feature structures that can be used as values of CAT), and its values are feature structures of sort *aspect*. *aspect* contains only atomic feature structures, and has the subsorts: *state*, *activity*, *culmact* (culminating activity), and *point*. *state* is in turn partitioned into: *lex.state* (lexical state), *progressive* (progressive state), and *cnsq.state* (consequent state). This agrees with the aspectual taxonomy of chapter 2. Following table 2.1 on page 26, (4.1) classifies the base form of “to land” as culminating activity.

The SPR, SUBJ, and COMPS features of (4.1) provide information about the specifier, subject, and complements with which the verb has to combine. Specifiers are determiners (e.g. “a”, “the”), and words like “much” (as in “much more”) and “too” (as in “too late”). Verbs do not admit specifiers, and hence the value of SPR in (4.1) is the empty list.

The SUBJ value of (4.1) means that the verb requires a noun-phrase as its subject. The NP[-PRD]_[1] in (4.1) has the same meaning as in [Pollard & Sag 94]. Roughly speaking, it is an abbreviation for a sign that corresponds to a noun phrase. The -PRD means that the noun phrase must be non-predicative (see section 4.9 below). The _[1] is intuitively a pointer to the world entity described by the noun phrase. Similarly, the COMPS value of (4.1) means that the verb requires as its complement a non-predicative prepositional phrase (section 4.8 below), introduced by “on”. The _[2] is intuitively a pointer to the world entity of the prepositional phrase (e.g. if the prepositional phrase is “on a runway”, the _[2] is a pointer to the runway).

The value of CONT in (4.1) represents the TOP predicate *landing-on*(β, τ_1, τ_2), where τ_1 and τ_2 are TOP terms corresponding to _[1] and _[2], and β is a TOP variable acting as an occurrence identifier (section 3.16).² The exact relation between HPSG feature structures and TOP expressions will be discussed in the following sections.

² I follow the approach of section 8.5.1 of [Pollard & Sag 94], whereby the RELATION feature is dropped, and its role is taken up by the sort of the feature structure.

4.2.2 Lexical rules

Lexical rules generate new lexical signs from existing ones. In section 4.7, for example, I introduce lexical rules that generate automatically lexical signs for (single-word) non-base verb forms (e.g. a sign for the simple past “*landed*”) from signs for base forms (e.g. (4.1)). This reduces the number of lexical signs that need to be listed in the grammar.

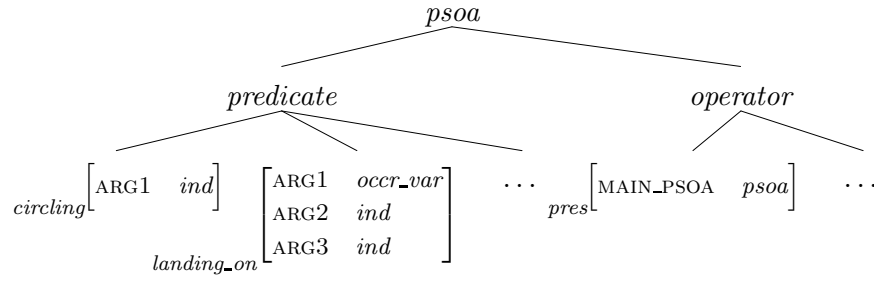
4.2.3 Schemata and principles

HPSG schemata specify basic patterns that are used when words or syntactic constituents combine to form larger constituents. For example, the *head-complement schema* is the pattern that is used when a verb combines with its complements (e.g. when “*landed*” combines with its complement “*on runway 2*”; in this case, the verb is the “head-daughter” of the constituent “*landed on runway 2*”). The *head-subject schema* is the one used when a verb phrase (a verb that has combined with its complements but not its subject) combines with its subject (e.g. when “*landed on runway 2*” combines with “*BA737*”; in this case, the verb phrase is the head-daughter of “*BA737 landed on runway 2*”). No modifications to the schemata of [Pollard & Sag 94] are introduced in this thesis, and hence schemata will not be discussed further.

HPSG principles control the propagation of feature values from the signs of words or syntactic constituents to the signs of their super-constituents. The *head feature principle*, for example, specifies that the sign of the super-constituent inherits the HEAD value of the head-daughter’s sign. This causes the sign of “*landed on runway 2*” to inherit the HEAD value of the sign of “*landed*”, and the same value to be inherited by the sign of “*BA737 landed on runway 2*”. This thesis uses simplified versions of Pollard and Sag’s semantics principle and constituent ordering principle (to be discussed in sections 4.9.1 and 4.13), and introduces one new principle (the aspect principle, to be discussed in section 4.11.1). All other principles are as in [Pollard & Sag 94].

4.3 Representing TOP yes/no formulae in HPSG

According to [Pollard & Sag 94], the CONT value of (4.1) should actually be (4.2).

Figure 4.1: Subsorts of *psoa*

$$(4.2) \quad \text{psoa} \left[\begin{array}{cc} \text{QUANTS} & \langle \rangle \\ \text{NUCLEUS} & \left[\begin{array}{cc} \text{ARG1} & \text{occr_var} \\ \text{ARG2} & \boxed{1} \\ \text{ARG3} & \boxed{2} \end{array} \right] \end{array} \right]$$

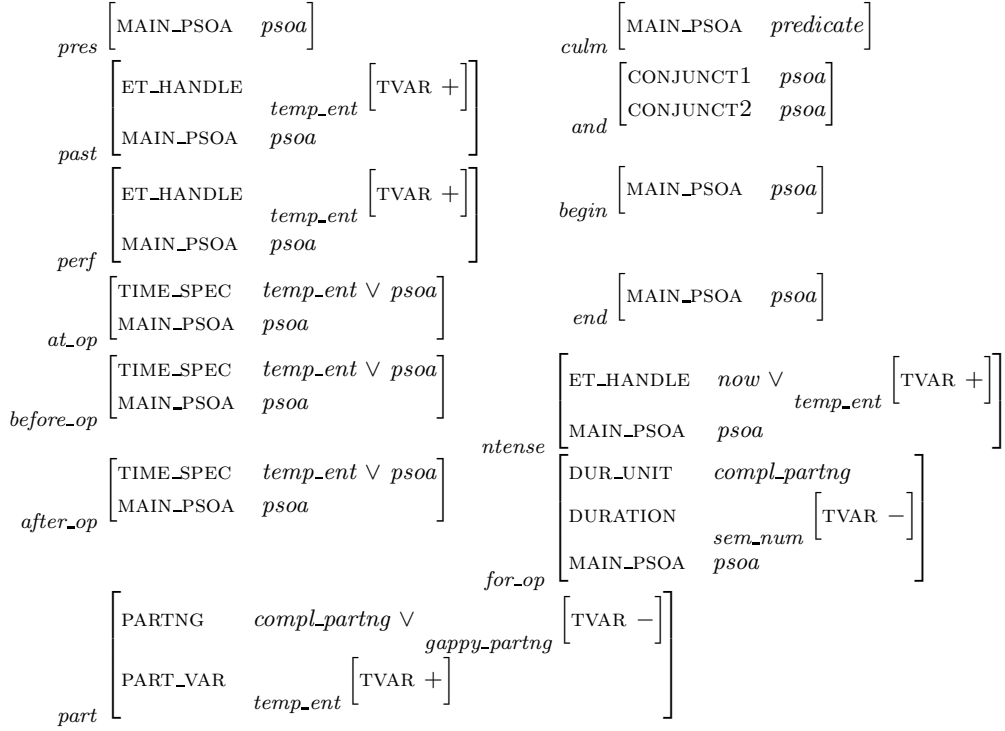
In [Pollard & Sag 94], feature structures of sort *psoa* have two features: QUANTS and NUCLEUS.³ QUANTS, which is part of HPSG’s quantifier storage mechanism, is not used in this thesis. This leaves only one feature (NUCLEUS) in *psoas*. For simplicity, NUCLEUS was also dropped, and the *psoa* sort was taken to contain the feature structures that would be values of NUCLEUS in [Pollard & Sag 94].

More precisely, in this thesis *psoa* has two subsorts: *predicate* and *operator* (figure 4.1). *predicate* contains feature structures that represent TOP predicates, while *operator* contains feature structures that represent all other TOP yes/no formulae. (Hence, *psoa* corresponds to all yes/no formulae.) *predicate* has domain-specific subsorts, corresponding to predicate functors used in the domain for which the NLITDB is configured. In the airport domain, for example, *landing_on* is a subsort of *predicate*. The feature structures in the subsorts of *predicate* have features named ARG1, ARG2, ARG3, etc. These represent the first, second, third, etc. arguments of the predicates. The values of ARG1, ARG2, etc. are of sort *ind* (*occr_var* is a subsort of *ind*). *ind* will be discussed further below.

The *operator* sort has thirteen subsorts, shown in figure 4.2. These correspond to the twelve TOP operators (*Fills* is ignored), plus one sort for conjunction.⁴ The order of the features in figure 4.2 corresponds to the order of the arguments of the TOP operators.

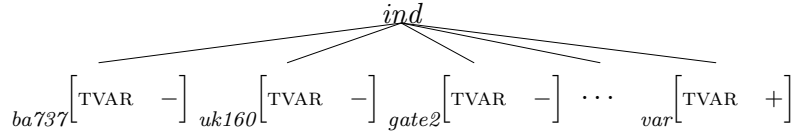
³ “*Psoa*” stands for “parameterised state of affairs”, a term from situation theory [Cooper *et al.* 90]. The semantic analysis here is not situation-theoretic, but the term “*psoa*” is still used for compatibility with [Pollard & Sag 94].

⁴ The sorts that correspond to the *At*, *Before*, *After*, and *For* operators are called *at_op*, *before_op*, *after_op*, and *for_op* to avoid name clashes with existing HPSG sorts.

Figure 4.2: Subsorts of *operator*

For example, the `ET_HANDLE` and `MAIN_PSOA` features of the *past* sort correspond to the first and second arguments respectively of TOP’s $Past[\beta, \phi]$. For simplicity, in the rest of this thesis I drop the $Part[\sigma, \beta, \nu_{ord}]$ version of *Part* (section 3.6), and I represent words like “yesterday” using TOP constants (e.g. *yesterday*) rather than expressions like $Part[day^c, \beta, -1]$. This is why there is no sort for $Part[\sigma, \beta, \nu_{ord}]$ in figure 4.2.

In [Pollard & Sag 94], feature structures of sort *ind* (called indices) have the features *person*, *number*, and *gender*, which are used to enforce person, number, and gender agreement. For simplicity, these features are ignored here, and no agreement checks are made. Pollard and Sag’s subsorts of *ind* (*ref*, *there*, *it*), which are used in HPSG’s binding theory, are also ignored here. In this thesis, indices represent TOP terms (they also represent gappy partitioning names, but let us ignore this temporarily). The situation is roughly speaking as in figure 4.3. For each TOP constant (e.g. *ba737*, *gate2*), there is a subsort of *ind* that represents that constant. There is also a subsort *var* of *ind*, whose indices represent TOP variables. A TVAR feature is used to distinguish indices that represent constants from indices that represent variables. All indices of constant-representing sorts (e.g. *ba737*, *uk160*) have their TVAR set to $-$. Indices of *var* have their TVAR set to $+$.

Figure 4.3: *ind* and its subsorts – simplified version

The fact that there is only one subsort (*var*) for TOP variables in figure 4.3 does not mean that only one TOP variable can be represented. *var* is a *sort* of feature structures, containing infinitely many feature-structure members. Although the members of *var* cannot be distinguished by their feature values (they all have TVAR set to +), they are still different; i.e. they are “structurally identical” but not “token-identical” (see chapter 1 of [Pollard & Sag 94]). Each one of the feature-structure members of *var* represents a different TOP variable. The subsorts that correspond to TOP constants also contain infinitely many different feature-structure members. In this case, however, all members of the same subsort are taken to represent the same constant. For example, any feature structure of sort *gate2* represents the TOP constant *gate2*.

4.4 More on the subsorts of *ind*

The subsorts of *ind* are actually more complicated than in figure 4.3. Natural language front-ends (e.g. MASQUE [Auxerre & Inder 86], TEAM [Grosz *et al.* 87], CLE [Alshawi 92], SYSTEMX [Cerccone *et al.* 93]) often employ a domain-dependent hierarchy of types of world entities. This hierarchy is typically used in disambiguation, and to detect semantically anomalous sentences like “Gate 2 departed from runway 1”. Here, a hierarchy of this kind is mounted under the *ind* sort. (Examples illustrating the use of this hierarchy are given in following sections.)

In the airport domain, there are temporal world entities (the Monday 16/10/95, the year 1995, etc.), and non-temporal world entities (flight BA737, gate 2, etc.). Indices representing temporal entities are classified into a *temp_ent* subsort of *ind*, while indices representing non-temporal entities are classified into *non_temp_ent* (see figure 4.4; ignore *partng* and its subsorts for the moment). *non_temp_ent* has in turn subsorts like *mass* (indices representing mass entities, e.g. foam or water), *flight_ent* (indices representing flights, e.g. BA737), etc. *flight_ent* has one subsort for each TOP constant that denotes a flight (e.g. *ba737*, *uk160*), plus one sort (*flight_ent_var*) whose indices

represent TOP variables that denote flights. The other children-sorts of *non-temp_ent* have similar subsorts.

temp_ent has subsorts like *minute_ent* (indices representing particular minutes, e.g. the 5:00pm minute of 1/1/91), *day_ent* (indices representing particular days), etc. *minute_ent* has one subsort for each TOP constant that denotes a particular minute (e.g. *5:00pm1/1/91*), plus one sort (*minute_ent_var*) whose indices represent TOP variables that denote particular minutes. The other children-sorts of *temp_ent* have similar subsorts. The indices of *other_temp_ent_var* (figure 4.4) represent TOP variables that denote temporal-entities which do not correspond to sister-sorts of *other_temp_ent_var* (*minute_ent*, *day_ent*, etc.). This is needed because not all TOP variables denote particular minutes, days, months, etc. In (4.3), for example, e^v denotes a past period that covers exactly a taxiing of UK160 to gate 1 (from start to completion). The taxiing may have started at 5:00pm on 1/1/95, and it may have been completed at 5:05pm on the same day. In that case, e^v denotes a period that is neither a minute-period, nor a day-period, nor a month-period, etc.

$$(4.3) \quad \text{Past}[e^v, \text{Culm}[\text{taxiing_to}(\text{occr}^v, \text{uk160}, \text{gate1})]]$$

occr_var contains indices that represent TOP variables used as occurrence identifiers (section 3.16). Indices of sorts that represent TOP constants (e.g. *foam*, *5:00pm1/1/91*, *Jun93* in figure 4.4) have their TVAR set to $-$. Indices of sorts that represent TOP variables (e.g. *flight_ent_var*, *minute_ent_var*, *other_temp_ent_var*, *occr_var*) have their TVAR set to $+$. There is also a special sort *now* (not shown in figure 4.4) that is used to represent the TOP expression *now** (section 3.13).

The sorts of figure 4.2 mirror the definitions of TOP's operators. For example, the *ntense* sort reflects that fact that the first argument of an *Ntense* operator must be *now** or a variable (TVAR $+$) denoting a period (*temp_ent*), while the second argument must be a yes/no formula (*psoa*). (The *sem_num* sort in *for_op* is a child-sort of *non-temp_ent*, with subsorts that represent the numbers 1, 2, 3, etc. The *compl_partng* and *gappy_partng* sorts in *for_op* and *part* are discussed below.)

The hierarchy under *ind* is domain-dependent. For example, in an application where the database contains information about a company, the subsorts of *non-temp_ent* would correspond to departments, managers, etc. I assume, however, that in all application domains, *ind* would have the children-sorts *temp_ent*, *non-temp_ent*, *occr_var*,

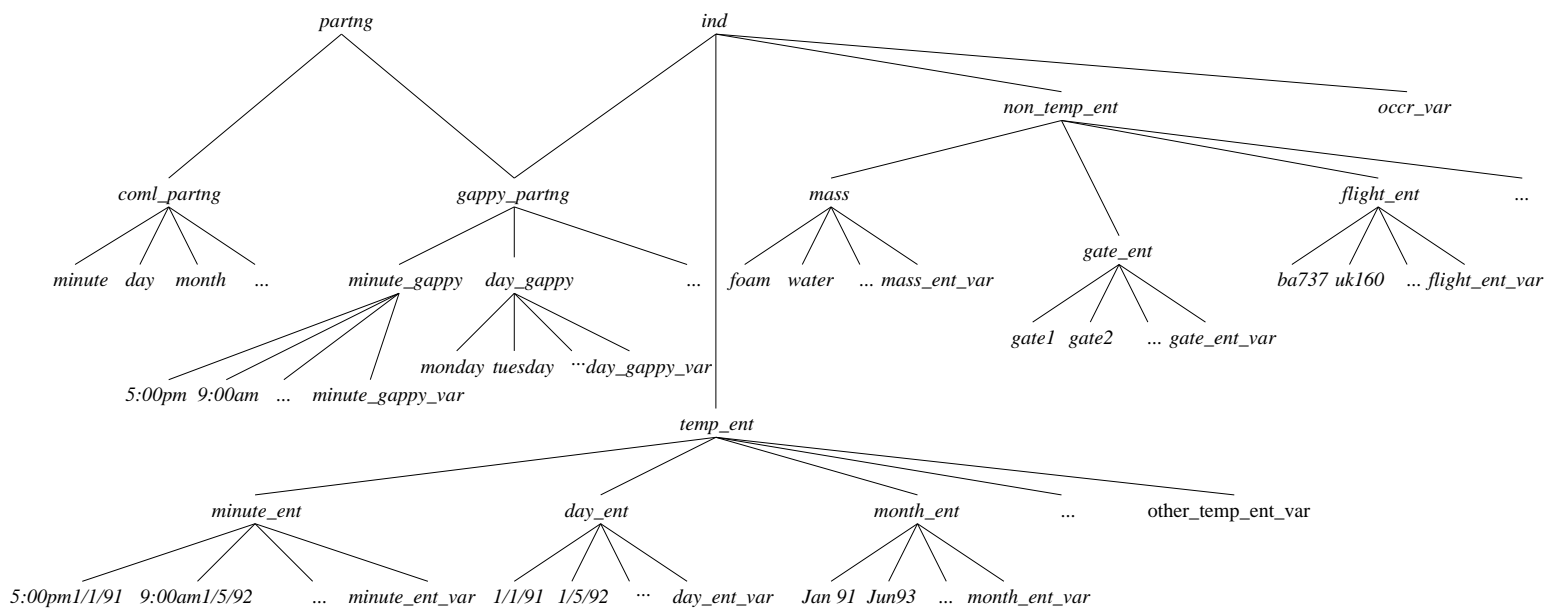


Figure 4.4: *partng*, *ind*, and their subsorts

gappy_partng (to be discussed below), and possibly more. I also assume that the subsorts of *partng* (see below) and *temp_ent* would have the general form of figure 4.4, though they would have to be adjusted to reflect the partitionings and temporal entities used in the particular application.

I now turn to the *partng* sort of figure 4.4, which has the subsorts *compl_partng* and *gappy_partng* (these three sorts do not exist in [Pollard & Sag 94]). For each TOP complete or gappy partitioning name (e.g. *minute^c*, *day^c*, *5:00pm^g*, *monday^g*) there is a leaf-subsort of *compl_partng* or *gappy_partng* respectively that represents that name. (The leaf-subsorts of *gappy_partng* are also used to represent some TOP terms; this is discussed below.) In figure 4.4, the sorts *5:00pm*, *9:00am*, etc. are grouped under *minute_gappy* to reflect the fact that the corresponding partitionings contain minute-periods. (I assume here that these partitioning names denote the obvious partitionings.) Similarly, *monday*, *tuesday*, etc. are grouped under *day_gappy* to reflect the fact that the corresponding partitionings contain day-periods. Section 4.12 provides examples where sorts like *minute_gappy* and *day_gappy* prove useful.

Apart from gappy partitioning names, the subsorts of *gappy_partng* are also used to represent TOP terms that denote generic representatives of partitionings (section 3.18). (To allow the subsorts of *gappy_partng* to represent TOP terms, *gappy_partng* is not only a subsort of *partng*, but also of *ind*; see figure 4.4.) For example, (4.5) (that expresses the habitual reading of (4.4)) is represented as (4.6). In this case, the subsort *5:00pm* of *gappy_partng* represents the TOP constant *5:00pm*.

(4.4) BA737 departs (habitually) at 5:00pm

(4.5) $Pres[hab_departs_at(ba737, 5:00pm)]$

(4.6)
$$pres \left[\begin{array}{cc} MAIN_PSOA & hab_departs_at \left[\begin{array}{cc} ARG1 & ba737 \left[\begin{array}{c} TVAR \\ - \end{array} \right] \\ ARG2 & 5:00pm \left[\begin{array}{c} TVAR \\ - \end{array} \right] \end{array} \right] \end{array} \right]$$

In contrast, (4.8) (that expresses the non-habitual reading of (4.7)) is represented as (4.9). In this case, the subsort *5:00pm* of *gappy_partng* represents the TOP gappy partitioning name *5:00pm^g*. (It cannot represent a TOP term, because TOP terms cannot be used as first arguments of *Part* operators.) The \Box s in (4.9) mean that the values of PART_VAR and TIME_SPEC must be token-identical, i.e. they must represent the same TOP variable.

(4.7) BA737 departed (actually) at 5:00pm.

(4.8) $Part[5:00pm^g, fv^v] \wedge At[fv^v, Past[e^v, depart(ba737)]]$

(4.9)
$$\left[\begin{array}{c} \text{CONJUNCT1} \\ \text{part} \\ \text{CONJUNCT2} \\ \text{and} \end{array} \left[\begin{array}{c} \text{PARTNG} \\ \text{PART_VAR} \\ \text{minute_ent_var} \\ \text{TIME_SPEC} \\ \text{MAIN_PSOA} \\ \text{past} \end{array} \left[\begin{array}{c} 5:00pm \\ \text{minute_ent_var} \\ \text{ET_HANDLE} \\ \text{MAIN_PSOA} \\ \text{depart} \end{array} \left[\begin{array}{c} \text{TVAR } - \\ \text{TVAR } + \\ \text{TVAR } + \\ \text{ARG1} \\ \text{ba737} \end{array} \left[\begin{array}{c} \text{TVAR } - \\ \text{TVAR } - \end{array} \right] \right] \right] \right] \right]$$

The *minute_gappy* and *gappy_var* sorts of figure 4.4 are used only to represent TOP variables that denote generic representatives of unknown *minute_gappy* or *day_gappy* partitionings. The t^v variable of (4.11), for example, denotes the generic representative of an unknown *minute_gappy* partitioning. (If BA737 departs habitually at 5:00pm, t^v denotes the generic representative of the $5:00pm^g$ partitioning, the same generic representative that the $5:00pm$ constant of (4.5) denotes.) The $Pres[hab_departs_at(ba737, t^v)]$ part of (4.11) is represented as (4.12). (The feature-structure representation of quantifiers will be discussed in section 4.5.)

(4.10) When does BA737 (habitually) depart?

(4.11) $?t^v Pres[hab_departs_at(ba737, t^v)]$

(4.12)
$$\left[\begin{array}{c} \text{MAIN_PSOA} \\ \text{pres} \end{array} \left[\begin{array}{c} \text{hab_departs_at} \end{array} \left[\begin{array}{c} \text{ARG1} \\ \text{ARG2} \end{array} \left[\begin{array}{c} ba737 \\ \text{minute_gappy_var} \end{array} \left[\begin{array}{c} \text{TVAR } - \\ \text{TVAR } + \end{array} \right] \right] \right] \right] \right]$$

The indices of sorts like *minute_gappy_var* and *day_gappy_var* have their TVAR set to +. The indices of all other leaf-subsorts of *gappy_partng* (e.g. *5:00pm*, *monday*) have their TVAR set to −.

4.5 Representing TOP quantifiers in HPSG

TOP yes/no formulae are represented in the HPSG version of this thesis as feature-structures of sort *psoa* (figure 4.1). To represent TOP wh-formulae (formulae with interrogative or interrogative-maximal quantifiers) additional feature-structure sorts are needed. I discuss these below.

Feature structures of sort *quant* represent unresolved quantifiers (quantifiers whose scope is not known yet). They have two features: DET and RESTIND (restricted index), as shown in (4.13). The DET feature shows the type of the quantifier. In this thesis, DET can have the values *exists* (existential quantifier), *interrog* (interrogative quantifier), and *interrog_maxl* (interrogative-maximal quantifier). (Apart from the values of DET, *quant* is as in [Pollard & Sag 94].)

$$(4.13) \quad \text{quant} \left[\begin{array}{c} \text{DET} \quad \text{exists} \vee \text{interrog} \vee \text{interrog_maxl} \\ \text{RESTIND} \quad \left[\begin{array}{c} \text{INDEX} \quad \text{ind} \left[\begin{array}{c} \text{TVAR} \quad + \end{array} \right] \\ \text{RESTR} \quad \text{set}(\text{psoa}) \end{array} \right] \end{array} \right]$$

The values of RESTIND are feature structures of sort *nom_obj* (nominal object).⁵ These have the features INDEX (whose values are of sort *ind*) and RESTR (whose values are sets of *psoa*s). When a *nom_obj* feature structure is the value of RESTIND, the INDEX corresponds to the TOP variable being quantified, and the RESTR corresponds to the restriction of the quantifier. (If the RESTR set contains more than one *psoa*s, the *psoa*-elements of the set are treated as forming a conjunction.) For example, (4.14) represents (4.15).

$$(4.14) \quad \text{quant} \left[\begin{array}{c} \text{DET} \quad \text{interrog} \\ \text{RESTIND} \quad \left[\begin{array}{c} \text{INDEX} \quad \text{ind} \left[\begin{array}{c} \text{TVAR} \quad + \end{array} \right] \boxed{1} \\ \text{RESTR} \quad \left\{ \text{flight} \left[\begin{array}{c} \text{ARG1} \quad \boxed{1} \end{array} \right] \right\} \end{array} \right] \end{array} \right]$$

$$(4.15) \quad ?f^v \text{ flight}(f^v)$$

Although TOP does not use explicit existential quantifiers (universal quantification is not supported, and TOP variables can be thought of as existentially quantified), the HPSG version of this thesis employs explicit existential quantifiers (*quants* whose DET is *exists*) for compatibility with [Pollard & Sag 94]. These explicit existential quantifiers are removed when extracting TOP formulae from signs (this is discussed in section 4.6 below).

⁵ In [Pollard & Sag 94], *nom_obj* has the subsorts *npro* (non-pronoun) and *pron* (pronoun). These subsorts are not used in this thesis.

4.6 Extracting TOP formulae from HPSG signs

The parser maps each question to a sign. (Multiple signs are generated when the parser understands a question to be ambiguous.) For example, “Which inspector was at gate 2?” is mapped to (4.16) (exactly how (4.16) is generated will become clearer in the following sections; see also the comments about *Ntenses* in section 4.9.1 below).

$$(4.16) \quad \left[\begin{array}{l} \text{PHON} \quad \langle \text{which, inspector, was, at, gate2} \rangle \\ \\ \text{SYNSEM} \mid \text{LOC} \quad \left[\begin{array}{l} \text{CAT} \quad \left[\begin{array}{l} \text{HEAD} \quad \left[\begin{array}{l} \text{VFORM} \quad \text{fin} \\ \text{AUX} \quad + \end{array} \right] \\ \text{verb} \end{array} \right] \\ \text{ASPECT} \quad \text{lex_state} \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \rangle \\ \text{COMPS} \quad \langle \rangle \end{array} \right] \\ \\ \text{CONT} \quad \left[\begin{array}{l} \text{ET_HANDLE} \quad \left[\begin{array}{l} \text{TVAR} \quad + \end{array} \right] \\ \text{temp_ent} \\ \text{MAIN_PSOA} \quad \left[\begin{array}{l} \text{ARG1} \quad \boxed{1} \\ \text{ARG2} \quad \text{gate2} \end{array} \right] \\ \text{past} \quad \text{located_at} \end{array} \right] \end{array} \right] \\ \\ \text{QSTORE} \quad \left\{ \begin{array}{l} \left[\begin{array}{l} \text{DET} \quad \text{interrog} \\ \\ \text{RESTIND} \quad \left[\begin{array}{l} \text{INDEX} \quad \left[\begin{array}{l} \text{TVAR} \quad + \end{array} \right] \boxed{1} \end{array} \right] \\ \text{RESTR} \quad \left\{ \begin{array}{l} \text{person_ent} \\ \text{inspector} \end{array} \right\} \left[\begin{array}{l} \text{ARG1} \quad \boxed{1} \end{array} \right] \end{array} \right] \end{array} \right\} \\ \text{quant} \quad \text{nom_obj} \end{array} \right\} \end{array} \right]$$

Apart from the features that were discussed in section 4.2, signs also have the feature QSTORE, whose values are sets of *quants* (section 4.5). The CONT value of signs that correspond to questions is of sort *psoa*, i.e. it represents a TOP yes/no formula. In the HPSG version of this thesis, the QSTORE value represents quantifiers that must be “inserted” in front of the formula of CONT. In the prototype NLITDB (to be discussed in chapter 6), there is an “extractor” of TOP formulae that examines the CONT and QSTORE features of the question’s sign, and generates the corresponding TOP formula. This is a trivial process, which I discuss only at an abstract level: the extractor first examines recursively the features and feature values of CONT, rewriting them in term notation (in (4.16), this generates (4.17)); then, for each element of QSTORE, the extractor adds a suitable quantifier in front of the formula of CONT (in (4.16), this transforms (4.17) into (4.18)).

$$(4.17) \quad \text{Past}[e^v, \text{located_at}(p^v, \text{gate2})]$$

$$(4.18) \quad ?p^v \text{inspector}(p^v) \wedge \text{Past}[e^v, \text{located_at}(p^v, \text{gate2})]$$

In the case of elements of QSTORE that correspond to existential quantifiers, no explicit existential quantifier is added to the formula of CONT (only the expression that corresponds to the RESTR of the *quant*-element is added). For example, if the DET of (4.16) were *exists*, (4.18) would be (4.19).

$$(4.19) \quad \textit{inspector}(p^v) \wedge \textit{Past}[e^v, \textit{located_at}(p^v, \textit{gate2})]$$

The extracted formula then undergoes an additional post-processing phase (to be discussed in section 4.17). This is a collection of transformations that need to be applied to some of the extracted formulae. (In (4.18) and (4.19), the post-processing has no effect.)

4.7 Verb forms

I now present the treatment of the various linguistic constructs, starting from verb forms (simple present, past continuous, etc.). (Pollard and Sag do not discuss temporal linguistic mechanisms.)

4.7.1 Single-word verb forms

Let us first examine the lexical rules that generate signs for (single-word) non-base verb forms from signs for base forms. The signs for simple present forms are generated by (4.20).

(4.20) SIMPLE PRESENT LEXICAL RULE:

$$\begin{array}{c} \left[\begin{array}{c} \text{PHON} \quad \langle \lambda \rangle \\ \text{SYNSEM} \mid \text{LOC} \end{array} \left[\begin{array}{c} \text{CAT} \left[\begin{array}{c} \text{HEAD} \left[\begin{array}{c} \text{VFORM} \quad bse \\ \text{AUX} \quad - \end{array} \right] \\ \text{ASPECT} \quad \textit{verb} \quad \textit{lex_state} \end{array} \right] \\ \text{CONT} \quad \boxed{1} \end{array} \right] \right] \right] \\ \Downarrow \\ \left[\begin{array}{c} \text{PHON} \quad \langle \textit{morph}(\lambda, \textit{simple_present}) \rangle \\ \text{SYNSEM} \mid \text{LOC} \end{array} \left[\begin{array}{c} \text{CAT} \left[\begin{array}{c} \text{HEAD} \left[\begin{array}{c} \text{VFORM} \quad \textit{fin} \\ \text{AUX} \quad - \end{array} \right] \\ \text{ASPECT} \quad \textit{verb} \quad \textit{lex_state} \end{array} \right] \\ \text{CONT} \quad \textit{pres} \left[\begin{array}{c} \text{MAIN_PSOA} \quad \boxed{1} \end{array} \right] \end{array} \right] \right] \right] \end{array}$$

(4.20) means that for each lexical sign that matches the first feature structure (the “left hand side”, LHS) of the rule, a new lexical sign should be generated as shown in the second feature structure (the “right hand side”, RHS) of the rule. (Following standard HPSG notation, I write SYNSEM|LOC to refer to the LOC feature of the value of SYNSEM .) The HEADS of the LHS and RHS mean that the original sign must correspond to the base form of a non-auxiliary verb (auxiliary verbs are treated separately), and that the resulting sign corresponds to a finite verb form (a form that does not need to combine with an auxiliary verb). The CONT of the new sign is the same as the CONT of the original one, except that it contains an additional *Pres* operator. Features of the original sign not shown in the LHS (e.g. SUBJ, COMPS) have the same values in the generated sign. (4.20) requires the original sign to correspond to a (lexical) state base form. No simple present signs are generated for verbs whose base forms are not states. This is in accordance with the assumption of section 2.5.1 that the simple present can be used only with state verbs.

$\text{morph}(\lambda, \text{simple_present})$ denotes a morphological transformation that generates the simple present form (e.g. “contains”) from the base form (e.g. “contain”). The prototype NLITDB actually employs two different simple present lexical rules. These generate signs for singular and plural simple present forms respectively. As mentioned in sections 2.13 and 4.3, plurals are treated semantically as singulars, and no number-agreement checks are made. Hence, the two lexical rules differ only in the PHON values of the generated signs.

(4.21) shows the base form sign of “to contain” in the airport domain. From (4.21), (4.20) generates (4.22). The *tank_ent* and *mass_ent* in (4.21) and (4.22) mean that the indices introduced by the subject and the object must be of sort *tank_ent* and *mass_ent* respectively (*tank_ent* is a sister of *flight_ent* in figure 4.4). Hence, the semantically anomalous “Gate 2 contains water.” (where the subject introduces an index of sort *gate2*, which is not a subsort of *tank_ent*) would be rejected. All lexical signs of verb forms have their QSTORE set to $\{\}$. For simplicity, I do not show the QSTORE feature here.

$$(4.21) \quad \left[\begin{array}{cc} \text{PHON} & \langle \text{contain} \rangle \\ \text{SYNSEM} \mid \text{LOC} & \left[\begin{array}{cc} \text{CAT} & \left[\begin{array}{cc} \text{HEAD} & \left[\begin{array}{cc} \text{VFORM} & bse \\ \text{AUX} & - \end{array} \right] \\ \text{verb} & \\ \text{ASPECT} & lex_state \\ \text{SPR} & \langle \rangle \\ \text{SUBJ} & \langle \text{NP}[-\text{PRD}]_{\text{tank_ent}[1]} \rangle \\ \text{COMPS} & \langle \text{NP}[-\text{PRD}]_{\text{mass_ent}[2]} \rangle \end{array} \right] \\ \text{CONT} & \left[\begin{array}{cc} \text{ARG1} & [1] \\ \text{ARG2} & [2] \end{array} \right] \\ \text{contains} & \end{array} \right] \end{array} \right]$$

$$(4.22) \quad \left[\begin{array}{cc} \text{PHON} & \langle \text{contains} \rangle \\ \text{SYNSEM} \mid \text{LOC} & \left[\begin{array}{cc} \text{CAT} & \left[\begin{array}{cc} \text{HEAD} & \left[\begin{array}{cc} \text{VFORM} & fin \\ \text{AUX} & - \end{array} \right] \\ \text{verb} & \\ \text{ASPECT} & lex_state \\ \text{SPR} & \langle \rangle \\ \text{SUBJ} & \langle \text{NP}[-\text{PRD}]_{\text{tank_ent}[1]} \rangle \\ \text{COMPS} & \langle \text{NP}[-\text{PRD}]_{\text{mass_ent}[2]} \rangle \end{array} \right] \\ \text{CONT} & \left[\begin{array}{cc} \text{MAIN_PSOA} & \left[\begin{array}{cc} \text{ARG1} & [1] \\ \text{ARG2} & [2] \end{array} \right] \\ \text{pres} & \text{contains} \end{array} \right] \end{array} \right] \end{array} \right]$$

The simple past signs of culminating activity verbs are generated by (4.23), shown below. The simple past signs of non-culminating activity verbs are generated by a lexical rule that is similar to (4.23), except that it does not introduce a *Culm* operator in the resulting sign.

The signs of past participles (e.g. “*inspected*” in “*Who had inspected BA737?*”) are generated by two lexical rules which are similar to the simple past ones. There is a rule for culminating activity verbs (which introduces a *Culm* in the past participle sign), and a rule for non-culminating activity verbs (that introduces no *Culm*). Both rules do not introduce *Past* operators. The generated signs have their *VFORM* set to *psp* (past participle), and the same *ASPECT* as the base signs, i.e. their *ASPECT* is not changed to *cnsq_state* (consequent state). The shift to consequent state takes place when the auxiliary “*had*” combines with the past participle (this will be discussed in section 4.7.2).

(4.23) SIMPLE PAST LEXICAL RULE (CULMINATING ACTIVITY BASE FORM):

$$\begin{array}{c}
\left[\begin{array}{c} \text{PHON} \quad \langle \lambda \rangle \\ \text{SYNSEM} \mid \text{LOC} \end{array} \left[\begin{array}{c} \text{CAT} \left[\begin{array}{c} \text{HEAD} \left[\begin{array}{c} \text{VFORM} \quad bse \\ \text{AUX} \quad - \end{array} \right] \\ \text{ASPECT} \quad verb \quad culmact \end{array} \right] \\ \text{CONT} \quad \boxed{1} \end{array} \right] \right] \right] \\
\Downarrow \\
\left[\begin{array}{c} \text{PHON} \quad \langle morph(\lambda, simple_past) \rangle \\ \text{SYNSEM} \mid \text{LOC} \end{array} \left[\begin{array}{c} \text{CAT} \left[\begin{array}{c} \text{HEAD} \left[\begin{array}{c} \text{VFORM} \quad fn \\ \text{AUX} \quad - \end{array} \right] \\ \text{ASPECT} \quad verb \quad culmact \end{array} \right] \\ \text{CONT} \left[\begin{array}{c} \text{ET_HANDLE} \quad temp_ent \quad \left[\text{TVAR} \quad + \right] \\ \text{MAIN_PSOA} \quad culm \quad \left[\text{MAIN_PSOA} \quad \boxed{1} \right] \end{array} \right] \\ \text{past} \end{array} \right] \right] \right]
\end{array}$$

The signs for present participles (e.g. “servicing” in “Which company is servicing BA737?”) are generated by (4.24). The present participle signs are the same as the base ones, except that their VFORM is *prp* (present participle), and their ASPECT is *progressive* (progressive state).

(4.24) PRESENT PARTICIPLE LEXICAL RULE:

$$\begin{array}{c}
\left[\begin{array}{c} \text{PHON} \quad \langle \lambda \rangle \\ \text{SYNSEM} \mid \text{LOC} \end{array} \left[\begin{array}{c} \text{CAT} \left[\begin{array}{c} \text{HEAD} \left[\begin{array}{c} \text{VFORM} \quad bse \\ \text{AUX} \quad - \end{array} \right] \\ \text{ASPECT} \quad verb \quad aspect \end{array} \right] \\ \text{CONT} \quad \boxed{1} \end{array} \right] \right] \right] \\
\Downarrow \\
\left[\begin{array}{c} \text{PHON} \quad \langle morph(\lambda, present_participle) \rangle \\ \text{SYNSEM} \mid \text{LOC} \end{array} \left[\begin{array}{c} \text{CAT} \left[\begin{array}{c} \text{HEAD} \left[\begin{array}{c} \text{VFORM} \quad prp \\ \text{AUX} \quad - \end{array} \right] \\ \text{ASPECT} \quad verb \quad progressive \end{array} \right] \\ \text{CONT} \quad \boxed{1} \end{array} \right] \right] \right]
\end{array}$$

Gerund signs are generated by a lexical rule that is similar to (4.24), except that the generated signs retain the ASPECT of the original ones, and have their VFORM set to *ger*. In English, there is no morphological distinction between gerunds and present participles. HPSG and most traditional grammars (e.g. [Thomson & Martinet 86]),

however, distinguish between the two. In (4.25), the “*inspecting*” is the gerund of “*to inspect*”, while in (4.26), the “*inspecting*” is the present participle.

(4.25) J.Adams finished inspecting BA737.

(4.26) J.Adams was inspecting BA737.

The fact that gerund signs retain the ASPECT of the base signs is used in the treatment of “*to finish*” (section 2.6). The simple past “*finished*” receives multiple signs. (These are generated from corresponding base form signs by the simple past lexical rules.) (4.27) is used when “*finished*” combines with a culminating activity verb phrase, and (4.28) when it combines with a state or activity verb phrase.

$$\begin{array}{l}
 (4.27) \quad \left[\begin{array}{c} \text{PHON} \quad \langle \textit{finished} \rangle \\ \text{SYNSEM} \mid \text{LOC} \end{array} \left[\begin{array}{c} \text{CAT} \left[\begin{array}{c} \text{HEAD} \left[\begin{array}{c} \text{VFORM} \quad \textit{fin} \\ \text{AUX} \quad - \end{array} \right] \\ \textit{verb} \\ \text{ASPECT} \quad \textit{point} \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \boxed{1} \rangle \\ \text{COMPS} \quad \langle \text{VP}[\text{SUBJ} \langle \boxed{1} \rangle, \text{VFORM} \textit{ger}, \text{ASPECT} \textit{culmact}] : \boxed{2} \rangle \end{array} \right] \\ \text{CONT} \left[\begin{array}{c} \text{ET_HANDLE} \quad \textit{temp_ent} \left[\text{TVAR} \quad + \right] \\ \text{MAIN_PSOA} \quad \textit{end} \left[\text{MAIN_PSOA} \quad \textit{culm} \left[\text{MAIN_PSOA} \quad \boxed{2} \right] \right] \end{array} \right] \\ \textit{past} \end{array} \right] \right]
 \end{array}$$

$$\begin{array}{l}
 (4.28) \quad \left[\begin{array}{c} \text{PHON} \quad \langle \textit{finished} \rangle \\ \text{SYNSEM} \mid \text{LOC} \end{array} \left[\begin{array}{c} \text{CAT} \left[\begin{array}{c} \text{HEAD} \left[\begin{array}{c} \text{VFORM} \quad \textit{fin} \\ \text{AUX} \quad - \end{array} \right] \\ \textit{verb} \\ \text{ASPECT} \quad \textit{point} \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \boxed{1} \rangle \\ \text{COMPS} \quad \langle \text{VP}[\text{SUBJ} \langle \boxed{1} \rangle, \text{VFORM} \textit{ger}, \text{ASPECT} \textit{state} \vee \textit{activity}] : \boxed{2} \rangle \end{array} \right] \\ \text{CONT} \left[\begin{array}{c} \text{ET_HANDLE} \quad \textit{temp_ent} \left[\text{TVAR} \quad + \right] \\ \text{MAIN_PSOA} \quad \textit{end} \left[\text{MAIN_PSOA} \quad \boxed{2} \right] \end{array} \right] \\ \textit{past} \end{array} \right] \right]
 \end{array}$$

In (4.27), the $\text{VP}[\text{SUBJ} \langle \boxed{1} \rangle, \text{VFORM} \textit{ger}, \text{ASPECT} \textit{culmact}] : \boxed{2}$ means that “*finished*” requires as its complement a gerund verb phrase (a gerund that has combined with its complements but not its subject) whose aspect is culminating activity. The $\boxed{1}$ of COMPS points to a description of the required subject of the gerund verb phrase, and

the $\boxed{2}$ is a pointer to the CONT value of the sign of the gerund verb phrase. The two $\boxed{1}$ s in (4.27) have the effect that “*finished*” requires as its subject whatever the gerund verb phrase requires as its subject. The two $\boxed{2}$ s cause the sign of “*finished*” to inherit the CONT value of the sign of the gerund verb phrase, but with additional *Past*, *End*, and *Culm* operators. (4.28) is similar, but it introduces no *Culm*.

In (4.25), the sign of the gerund “*inspecting*” retains the ASPECT of the base sign, which in the airport domain is *culmact*. The sign of the gerund verb phrase “*inspecting BA737*” inherits the *culmact* ASPECT of the gerund sign (following the aspect principle, to be discussed in section 4.11.1). Hence, (4.27) is used. This causes (4.25) to receive a sign whose CONT represents (4.29), which requires the inspection to have been completed.

$$(4.29) \quad \textit{Past}[e^v, \textit{End}[\textit{Culm}[\textit{inspecting}(\textit{occr}^v, \textit{jadams}, \textit{ba737})]]]]$$

In (4.30), the sign of “*circling*” inherits the *activity* ASPECT of the base sign, causing (4.28) to be used. This leads to (4.31), which does not require any completion to have been reached.

$$(4.30) \quad \textit{BA737 finished circling.}$$

$$(4.31) \quad \textit{Past}[e^v, \textit{End}[\textit{circling}(\textit{ba737})]]$$

There is also a sign of the simple past “*finished*” for the case where the gerund verb phrase is a point. In that case, the CONT of the sign of “*finished*” is identical to the the CONT of the sign of the gerund verb phrase, i.e. the “*finished*” has no semantic contribution. This is in accordance with the arrangements of section 2.6. The signs of “*started*”, “*stopped*”, and “*began*” are similar, except that they introduce *Begin* operators instead of *End* ones. Unlike “*finished*”, the signs of “*stopped*” do not introduce *Culm* operators when “*stopped*” combines with culminating activities, reflecting the fact that there is no need for a completion to have been reached.

4.7.2 Auxiliary verbs and multi-word verb forms

I now move on to auxiliary verbs and multi-word verb forms (e.g. “*had departed*”, “*is inspecting*”). (4.32) shows the sign of the simple past auxiliary “*had*”. According to (4.32), “*had*” requires as its complement a past participle verb phrase. The $\boxed{1}$ s mean

that “*had*” requires as its subject whatever the past participle verb phrase requires as its subject. The $\boxed{2}$ s mean that the MAIN_PSOA value of the *perf* is the CONT value of the sign of the past participle verb phrase.

$$(4.32) \left[\begin{array}{c} \text{PHON} \quad \langle \textit{had} \rangle \\ \\ \text{SYNSEM} \mid \text{LOC} \end{array} \left[\begin{array}{c} \text{CAT} \\ \\ \text{CONT} \end{array} \left[\begin{array}{c} \text{HEAD} \quad \left[\begin{array}{c} \text{VFORM} \quad \textit{fin} \\ \text{AUX} \quad + \end{array} \right] \\ \textit{verb} \\ \text{ASPECT} \quad \textit{cnsq_state} \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \boxed{1} \rangle \\ \text{COMPS} \quad \langle \text{VP} [\text{SUBJ} \langle \boxed{1} \rangle, \text{VFORM} \textit{psp}] : \boxed{2} \rangle \\ \\ \text{ET_HANDLE} \quad \left[\begin{array}{c} \textit{temp_ent} \\ \text{TVAR} \quad + \end{array} \right] \\ \text{MAIN_PSOA} \quad \left[\begin{array}{c} \text{ET_HANDLE} \quad \left[\begin{array}{c} \textit{temp_ent} \\ \text{TVAR} \quad + \end{array} \right] \\ \text{MAIN_PSOA} \quad \boxed{2} \end{array} \right] \end{array} \right] \right] \right]$$

In the airport domain, the past participle “*departed*” receives multiple signs (for various habitual and non-habitual uses; these signs are generated from the corresponding base form signs by the lexical rules of section 4.7.1). The sign of (4.34) is used in (4.33).

(4.33) BA737 had departed.

$$(4.34) \left[\begin{array}{c} \text{PHON} \quad \langle \textit{departed} \rangle \\ \\ \text{SYNSEM} \mid \text{LOC} \end{array} \left[\begin{array}{c} \text{CAT} \\ \\ \text{CONT} \end{array} \left[\begin{array}{c} \text{HEAD} \quad \left[\begin{array}{c} \text{VFORM} \quad \textit{psp} \\ \text{AUX} \quad - \end{array} \right] \\ \textit{verb} \\ \text{ASPECT} \quad \textit{point} \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \text{NP} [-\text{PRD}] \textit{flight_ent} \boxed{3} \rangle \\ \text{COMPS} \quad \langle \rangle \\ \text{actLdepart} \quad \left[\begin{array}{c} \text{ARG1} \quad \boxed{3} \end{array} \right] \end{array} \right] \right] \right]$$

According to (4.34), “*departed*” requires no complements, i.e. it counts as a verb phrase, and can be used as the complement of “*had*”. When “*had*” combines with “*departed*”, the SUBJ of (4.32) becomes the same as the SUBJ of (4.34) (because of the $\boxed{1}$ s in (4.32)), and the MAIN_PSOA of the *perf* in (4.32) becomes the same as the CONT of (4.34) (because of the $\boxed{2}$ s in (4.32)). The resulting constituent “*had departed*” receives (4.35).

$$(4.35) \quad \left[\begin{array}{l} \text{PHON} \quad \langle \text{had, departed} \rangle \\ \text{SYNSEM} \mid \text{LOC} \end{array} \left[\begin{array}{l} \text{CAT} \left[\begin{array}{l} \text{HEAD} \left[\begin{array}{l} \text{VFORM} \quad \text{fin} \\ \text{AUX} \quad + \end{array} \right] \\ \text{verb} \\ \text{ASPECT} \quad \text{cnsq_state} \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \text{NP}[-\text{PRD}] \text{flight_ent} \boxed{3} \rangle \\ \text{COMPS} \quad \langle \rangle \end{array} \right] \\ \text{CONT} \left[\begin{array}{l} \text{ET_HANDLE} \quad \text{temp_ent} \left[\text{TVAR} \quad + \right] \\ \text{MAIN_PSOA} \left[\begin{array}{l} \text{ET_HANDLE} \quad \text{temp_ent} \left[\text{TVAR} \quad + \right] \\ \text{MAIN_PSOA} \quad \text{actl_depart} \left[\text{ARG1} \quad \boxed{3} \right] \end{array} \right] \end{array} \right] \\ \text{past} \quad \text{perf} \end{array} \right] \right]$$

The HPSG principles (including the semantics and aspect principles that will be discussed in sections 4.9.1 and 4.11.1) cause (4.35) to inherit the HEAD, ASPECT, SPR, SUBJ, and CONT values of (4.32). Notice that this causes the aspect of “*had departed*” to become consequent state (“*departed*” was a point). As will be discussed in section 4.9, the proper name “*BA737*” contributes an index that represents the flight BA737. When “*had departed*” combines with its subject “*BA737*”, the index of “*BA737*” becomes the ARG1 value of (4.35) (because of the $\boxed{3}$ s of (4.35)). This causes (4.33) to receive a sign whose CONT represents (4.36).

$$(4.36) \quad \text{Past}[e1^v, \text{Perf}[e2^v, \text{actl_depart}(\text{ba737})]]$$

As mentioned in sections 2.5.4 and 3.15, present perfect forms are treated semantically as simple past forms. This is why, unlike the sign of “*had*”, the sign of “*has*” (shown in (4.37)) does not introduce a *Perf* operator, and preserves the aspect of the past participle. This causes “*BA737 has departed.*” to receive the same TOP formula as “*BA737 departed.*”.

$$(4.37) \left[\begin{array}{c} \text{PHON} \quad \langle has \rangle \\ \\ \text{SYNSEM} \mid \text{LOC} \end{array} \left[\begin{array}{c} \text{CAT} \left[\begin{array}{c} \text{HEAD} \left[\begin{array}{c} \text{VFORM} \quad fin \\ \text{AUX} \quad + \end{array} \right] \\ \text{verb} \\ \text{ASPECT} \quad \boxed{1} \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \boxed{2} \rangle \\ \text{COMPS} \quad \langle \text{VP} [\text{SUBJ} \langle \boxed{2} \rangle, \text{VFORM} \quad psp, \text{ASPECT} \quad \boxed{1}] : \boxed{3} \rangle \end{array} \right] \\ \\ \text{CONT} \left[\begin{array}{c} \text{ET_HANDLE} \quad \left[\text{TVAR} \quad + \right] \\ \text{MAIN_PSOA} \quad \boxed{3} \end{array} \right] \\ \text{past} \end{array} \right] \right]$$

“Does” receives the sign of (4.38), which indicates that it requires as its complement a base verb phrase. The verb phrase must be a (lexical) state. (This is in accordance with the assumption of section 2.5.1 that the simple present can be used only with state verbs.) (4.38) and the (habitual) base sign of (4.39) cause (4.40) to receive (4.41).

$$(4.38) \left[\begin{array}{c} \text{PHON} \quad \langle does \rangle \\ \\ \text{SYNSEM} \mid \text{LOC} \end{array} \left[\begin{array}{c} \text{CAT} \left[\begin{array}{c} \text{HEAD} \left[\begin{array}{c} \text{VFORM} \quad fin \\ \text{AUX} \quad + \end{array} \right] \\ \text{verb} \\ \text{ASPECT} \quad \text{lex_state} \quad \boxed{1} \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \boxed{2} \rangle \\ \text{COMPS} \quad \langle \text{VP} [\text{SUBJ} \langle \boxed{2} \rangle, \text{VFORM} \quad bse, \text{ASPECT} \quad \boxed{1}] : \boxed{3} \rangle \end{array} \right] \\ \\ \text{CONT} \left[\begin{array}{c} \text{MAIN_PSOA} \quad \boxed{3} \end{array} \right] \\ \text{pres} \end{array} \right] \right]$$

$$(4.39) \left[\begin{array}{c} \text{PHON} \quad \langle service \rangle \\ \\ \text{SYNSEM} \mid \text{LOC} \end{array} \left[\begin{array}{c} \text{CAT} \left[\begin{array}{c} \text{HEAD} \left[\begin{array}{c} \text{VFORM} \quad bse \\ \text{AUX} \quad - \end{array} \right] \\ \text{verb} \\ \text{ASPECT} \quad \text{lex_state} \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \text{NP} [-\text{PRD}] \text{company_ent} \boxed{4} \rangle \\ \text{COMPS} \quad \langle \text{NP} [-\text{PRD}] \text{flight_ent} \boxed{5} \rangle \end{array} \right] \\ \\ \text{CONT} \left[\begin{array}{c} \text{ARG1} \quad \boxed{4} \\ \text{ARG2} \quad \boxed{5} \end{array} \right] \\ \text{hab_servicer_of} \end{array} \right] \right]$$

$$(4.40) \quad \text{Does Airserve service BA737?}$$

$$(4.41) \left[\begin{array}{c} \text{PHON} \quad \langle \text{Does, Airserve, service, BA737} \rangle \\ \\ \text{SYNSEM} \mid \text{LOC} \end{array} \left[\begin{array}{c} \text{CAT} \left[\begin{array}{c} \text{HEAD} \left[\begin{array}{c} \text{VFORM} \quad bse \\ \text{AUX} \quad + \end{array} \right] \\ \text{verb} \\ \text{ASPECT} \quad lex_state \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \rangle \\ \text{COMPS} \quad \langle \rangle \end{array} \right] \\ \\ \text{CONT} \left[\begin{array}{c} \text{MAIN_PSOA} \\ pres \quad hab_servicer_of \end{array} \left[\begin{array}{c} \text{ARG1} \quad airserve \\ \text{ARG2} \quad ba737 \end{array} \right] \end{array} \right] \end{array} \right]$$

In the airport domain, the base form of “to service” receives also a sign that corresponds to the non-habitual homonym. This is similar to (4.39), but it introduces the predicate functor *actl_servicing*, and its ASPECT is *culmact*. This sign cannot be used in (4.40), because (4.38) requires the verb-phrase complement to be a state not a culminating activity. This correctly predicts that (4.40) cannot be asking if Airserve is actually servicing BA737 at the present moment.

“Did” receives two signs: one for culminating-activity verb-phrase complements (shown in (4.42)), and one for state, activity, or point verb-phrase complements (this is similar to (4.42), but introduces no *Culm*). In both cases, a *Past* operator is added. In the case of culminating-activity complements, a *Culm* operator is added as well.

$$(4.42) \left[\begin{array}{c} \text{PHON} \quad \langle did \rangle \\ \\ \text{SYNSEM} \mid \text{LOC} \end{array} \left[\begin{array}{c} \text{CAT} \left[\begin{array}{c} \text{HEAD} \left[\begin{array}{c} \text{VFORM} \quad fin \\ \text{AUX} \quad + \end{array} \right] \\ \text{verb} \\ \text{ASPECT} \quad culmact \quad [1] \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle [2] \rangle \\ \text{COMPS} \quad \langle \text{VP} [\text{SUBJ} \quad \langle [2] \rangle, \text{VFORM} \quad bse, \text{ASPECT} \quad [1]] : [3] \rangle \end{array} \right] \\ \\ \text{CONT} \left[\begin{array}{c} \text{ET_HANDLE} \quad temp_ent \left[\text{TVAR} \quad + \right] \\ past \quad culm \left[\text{MAIN_PSOA} \quad [3] \right] \end{array} \right] \end{array} \right]$$

The non-habitual sign of “service” and (4.42) cause (4.43) to be mapped to (4.44), which requires Airserve to have actually serviced BA737 in the past. The habitual sign of (4.39) and the “did” sign for non-culminating activity complements cause (4.43) to be mapped to (4.45), which requires Airserve to have been a past habitual servicer of BA737.

(4.43) Did Airserve service BA737?

(4.44) $Past[e^v, Culm[actl_servicing(occr^v, airserve, ba737)]]$

(4.45) $Past[e^v, hab_servicer_of(airserve, ba737)]$

The sign for the auxiliary “is” is shown in (4.46). The present participle “servicing” receives two signs, a non-habitual one (shown in (4.47)) and a habitual one. The latter is similar to (4.47), but it introduces the functor *hab_servicer_of*, and its ASPECT is *lex_state*. (The two present participle signs are generated from the base ones by the present participle lexical rule of section 4.7.1.) (4.46) and (4.47) cause (4.48) to be mapped to (4.49), which requires Airserve to be actually servicing BA737 at the present. (4.46) and the habitual present participle sign cause (4.48) to be mapped to (4.50), which requires Airserve to be the current habitual servicer of BA737.

(4.46)
$$\left[\begin{array}{c} \text{PHON} \quad \langle is \rangle \\ \\ \text{SYNSEM} \mid \text{LOC} \end{array} \left[\begin{array}{c} \text{CAT} \\ \\ \text{CONT} \end{array} \left[\begin{array}{c} \text{HEAD} \quad \left[\begin{array}{c} \text{VFORM} \quad fin \\ \text{AUX} \quad + \end{array} \right] \\ \text{ASPECT} \quad progressive \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \boxed{1} \rangle \\ \text{COMPS} \quad \langle \text{VP}[\text{SUBJ} \langle \boxed{1} \rangle, \text{VFORM} \textit{prp}] : \boxed{2} \rangle \\ \text{CONT} \quad \left[\begin{array}{c} \text{MAIN_PSOA} \quad \boxed{2} \end{array} \right] \end{array} \right] \right] \right]$$

(4.47)
$$\left[\begin{array}{c} \text{PHON} \quad \langle servicing \rangle \\ \\ \text{SYNSEM} \mid \text{LOC} \end{array} \left[\begin{array}{c} \text{CAT} \\ \\ \text{CONT} \end{array} \left[\begin{array}{c} \text{HEAD} \quad \left[\begin{array}{c} \text{VFORM} \quad prp \\ \text{AUX} \quad - \end{array} \right] \\ \text{ASPECT} \quad culmact \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \text{NP}[-\text{PRD}]_{company_ent} \boxed{1} \rangle \\ \text{COMPS} \quad \langle \text{NP}[-\text{PRD}]_{flight_ent} \boxed{2} \rangle \\ \text{CONT} \quad \left[\begin{array}{c} \text{ARG1} \quad occr_var \\ \text{ARG2} \quad \boxed{1} \\ \text{ARG3} \quad \boxed{2} \end{array} \right] \end{array} \right] \right] \right]$$

(4.48) Airserve is servicing BA737.

(4.49) $Pres[actl_servicing(occr^v, airserve, ba737)]$

(4.50) $Pres[hab_servicer_of(airserve, ba737)]$

The sign for the auxiliary “was” is similar to (4.46), except that it introduces a *Past* operator instead of a *Pres* one.

4.8 Predicative and non-predicative prepositions

Following Pollard and Sag ([Pollard & Sag 87], p.65), prepositions receive separate signs for their predicative and non-predicative uses. In sentences like (4.51) and (4.52), where the prepositions introduce complements of “to be”, the prepositions are said to be predicative. In (4.53) and (4.54), where they introduce complements of other verbs, the prepositions are non-predicative.

(4.51) BA737 is at gate 2.

(4.52) BA737 was on runway 3.

(4.53) BA737 (habitually) arrives at gate 2.

(4.54) BA737 landed on runway 3.

Predicative prepositions introduce their own TOP predicates, while non-predicative prepositions have no semantic contribution.

4.8.1 Predicative prepositions

(4.55) shows the predicative sign of “at”. (The predicative signs of other prepositions are similar.) The PRD + shows that the sign is predicative. (PRD is also used to distinguish predicative adjectives and nouns; this will be discussed in sections 4.9 and 4.10.) PFORM reflects the preposition to which the sign corresponds. Signs for prepositional phrases inherit the PFORM of the preposition’s sign. This is useful in verbs that require prepositional phrases introduced by particular prepositions.

$$(4.55) \left[\begin{array}{cc} \text{PHON} & \langle at \rangle \\ \text{SYNSEM} | \text{LOC} & \left[\begin{array}{c} \text{CAT} \left[\begin{array}{c} \text{HEAD} \left[\begin{array}{c} \text{PFORM} \quad at \\ \text{PRD} \quad + \end{array} \right] \\ \text{prep} \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \text{NP}[-\text{PRD}] \text{[1]} \rangle \\ \text{COMPS} \quad \langle \text{NP}[-\text{PRD}] \text{[2]} \rangle \end{array} \right] \\ \text{CONT} \left[\begin{array}{c} \text{ARG1} \quad \text{[1]} \\ \text{ARG2} \quad non_temp_ent \text{[2]} \end{array} \right] \\ located_at \end{array} \right] \end{array} \right] \end{array}$$

According to (4.55), “at” requires a (non-predicative) noun-phrase (“BA737” in (4.51)) as its subject, and another one (“gate 2” in (4.51)) as its complement. As will be discussed in section 4.9, “BA737” and “gate 2” contribute indices that represent the corresponding world entities. The $\boxed{2}$ of (4.55) denotes the index of “gate 2”. (4.55) causes “at gate 2” to receive (4.56).

$$(4.56) \left[\begin{array}{cc} \text{PHON} & \langle at, gate2 \rangle \\ \text{SYNSEM} | \text{LOC} & \left[\begin{array}{cc} \text{CAT} & \left[\begin{array}{cc} \text{HEAD} & \left[\begin{array}{cc} \text{PFORM} & at \\ \text{PRD} & + \end{array} \right] \\ \text{prep} & \\ \text{SPR} & \langle \rangle \\ \text{SUBJ} & \langle \text{NP}[-\text{PRD}] \boxed{2} \rangle \\ \text{COMPS} & \langle \rangle \end{array} \right] \\ \text{CONT} & \left[\begin{array}{cc} \text{ARG1} & \boxed{1} \\ \text{ARG2} & gate2 \end{array} \right] \\ \text{located_at} & \end{array} \right] \end{array} \right]$$

Apart from (4.46) (which is used when “is” combines with a present-participle complement), “is” also receives (4.57) (which is used when “is” combines with predicative prepositional-phrases).

$$(4.57) \left[\begin{array}{cc} \text{PHON} & \langle is \rangle \\ \text{SYNSEM} | \text{LOC} & \left[\begin{array}{cc} \text{CAT} & \left[\begin{array}{cc} \text{HEAD} & \left[\begin{array}{cc} \text{VFORM} & fin \\ \text{AUX} & + \end{array} \right] \\ \text{verb} & \\ \text{ASPECT} & lex_state \\ \text{SPR} & \langle \rangle \\ \text{SUBJ} & \langle \boxed{3} \rangle \\ \text{COMPS} & \langle \text{PP}[\text{SUBJ } \langle \boxed{3} \rangle, \text{PRD } +] : \boxed{4} \rangle \end{array} \right] \\ \text{CONT} & \left[\begin{array}{cc} \text{MAIN_PSOA} & \boxed{4} \\ \text{pres} & \end{array} \right] \end{array} \right] \end{array} \right]$$

According to (4.57), “is” requires as its complement a predicative prepositional phrase (a predicative preposition that has combined with its complements but not its subject), like the “at gate 2” of (4.56). (4.56) and (4.57) cause (4.51) to receive (4.58).

$$(4.58) \quad \left[\begin{array}{cc} \text{PHON} & \langle BA737, is, at, gate2 \rangle \\ \text{SYNSEM} \mid \text{LOC} & \left[\begin{array}{cc} \text{CAT} & \left[\begin{array}{cc} \text{HEAD} & \left[\begin{array}{cc} \text{VFORM} & fin \\ \text{AUX} & + \end{array} \right] \\ \text{ASPECT} & lex_state \\ \text{SPR} & \langle \rangle \\ \text{SUBJ} & \langle \rangle \\ \text{COMPS} & \langle \rangle \end{array} \right] \\ \text{CONT} & \left[\begin{array}{cc} \text{MAIN_PSOA} & \left[\begin{array}{cc} \text{ARG1} & ba737 \\ \text{ARG2} & gate2 \end{array} \right] \\ \text{pres} & located_at \end{array} \right] \end{array} \right] \end{array} \right]$$

Like “is”, “was” receives two signs: one for present-participle complements (as in “BA737 was circling.”), and one for predicative prepositional-phrase complements (as in (4.52)). These are similar to the signs of “was”, but they introduce *Past* operators rather than *Pres* ones.

4.8.2 Non-predicative prepositions

The non-predicative sign of “at” is shown in (4.59). (The non-predicative signs of other prepositions are similar.) The $\boxed{1}$ is a pointer to the CONT value of the sign that corresponds to the noun-phrase complement of “at”. Notice that in this case the “at” has no semantic contribution (the “at” sign simply copies the CONT of the noun-phrase complement).

$$(4.59) \quad \left[\begin{array}{cc} \text{PHON} & \langle at \rangle \\ \text{SYNSEM} \mid \text{LOC} & \left[\begin{array}{cc} \text{CAT} & \left[\begin{array}{cc} \text{HEAD} & \left[\begin{array}{cc} \text{PFORM} & at \\ \text{PRD} & - \end{array} \right] \\ \text{prep} & \\ \text{SPR} & \langle \rangle \\ \text{SUBJ} & \langle \rangle \\ \text{COMPS} & \langle \text{NP}[-\text{PRD}]:\boxed{1} \rangle \end{array} \right] \\ \text{CONT} & \boxed{1} \end{array} \right] \end{array} \right]$$

(4.59) and the habitual sign of “arrives” of (4.60) cause (4.53) to receive (4.61).

$$(4.60) \quad \left[\begin{array}{c} \text{PHON} \quad \langle \text{arrives} \rangle \\ \\ \text{SYNSEM} \mid \text{LOC} \end{array} \left[\begin{array}{c} \text{CAT} \left[\begin{array}{c} \text{HEAD} \left[\begin{array}{c} \text{VFORM} \quad \text{fin} \\ \text{AUX} \quad - \end{array} \right] \\ \text{verb} \\ \text{ASPECT} \quad \text{lex_state} \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \text{NP}[-\text{PRD}] \text{flight_ent} \boxed{1} \rangle \\ \text{COMPS} \quad \langle \text{PP}[-\text{PRD}, \text{PFORM} \text{ at}] \text{gate_ent} \boxed{2} \rangle \end{array} \right] \\ \\ \text{CONT} \left[\begin{array}{c} \text{MAIN_PSOA} \left[\begin{array}{c} \text{ARG1} \quad \boxed{1} \\ \text{ARG2} \quad \boxed{2} \end{array} \right] \\ \text{pres} \quad \text{hab_arrive_at} \end{array} \right] \end{array} \right] \right]$$

$$(4.61) \quad \left[\begin{array}{c} \text{PHON} \quad \langle \text{BA737}, \text{arrives}, \text{at}, \text{gate2} \rangle \\ \\ \text{SYNSEM} \mid \text{LOC} \end{array} \left[\begin{array}{c} \text{CAT} \left[\begin{array}{c} \text{HEAD} \left[\begin{array}{c} \text{VFORM} \quad \text{fin} \\ \text{AUX} \quad - \end{array} \right] \\ \text{verb} \\ \text{ASPECT} \quad \text{lex_state} \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \rangle \\ \text{COMPS} \quad \langle \rangle \end{array} \right] \\ \\ \text{CONT} \left[\begin{array}{c} \text{MAIN_PSOA} \left[\begin{array}{c} \text{ARG1} \quad \text{ba737} \\ \text{ARG2} \quad \text{gate2} \end{array} \right] \\ \text{pres} \quad \text{hab_arrive_at} \end{array} \right] \end{array} \right] \right]$$

The (predicative and non-predicative) prepositional signs of this section are not used when prepositions introduce temporal adverbials (e.g. “BA737 departed at 5:00pm.”). There are additional prepositional signs for these cases (see section 4.11 below).

4.9 Nouns

Like prepositions, nouns receive different signs for their predicative and non-predicative uses. Nouns used in noun-phrase complements of “to be” (more precisely, the lexical heads of such noun-phrase complements), like the “*president*” of (4.62), are *predicative*. The corresponding noun phrases (e.g. “the *president*” of (4.62)) are also said to be predicative. In all other cases (e.g. “the *president*” of (4.63)), the nouns and noun phrases are *non-predicative*.

(4.62) J.Adams is the president.

(4.63) The president was at gate 2.

4.9.1 Non-predicative nouns

Let us first examine non-predicative nouns. (4.64) shows the sign of “*president*” that would be used in (4.63). The PRD value shows that the sign corresponds to a non-predicative use of the noun. The SPR value means that the noun requires as its specifier a determiner (e.g. “*a*”, “*the*”).

$$(4.64) \quad \left[\begin{array}{l} \text{PHON} \quad \langle \textit{president} \rangle \\ \\ \text{SYNSEM} \mid \text{LOC} \quad \left[\begin{array}{l} \text{CAT} \quad \left[\begin{array}{l} \text{HEAD} \quad \left[\begin{array}{l} \text{PRD} \quad - \\ \textit{noun} \end{array} \right] \\ \text{SPR} \quad \langle \text{LOC} \mid \text{CAT} \mid \text{HEAD} \quad \textit{det} \rangle \\ \text{SUBJ} \quad \langle \rangle \\ \text{COMPS} \quad \langle \rangle \end{array} \right] \\ \\ \text{CONT} \quad \left[\begin{array}{l} \text{INDEX} \quad \textit{person_ent} \boxed{1} \\ \text{RESTR} \quad \left\{ \begin{array}{l} \left[\begin{array}{l} \text{ET_HANDLE} \quad \left[\begin{array}{l} \text{TVAR} \quad + \end{array} \right] \vee \textit{now} \\ \textit{temp_ent} \end{array} \right] \\ \left[\begin{array}{l} \text{MAIN_PSOA} \quad \left[\begin{array}{l} \text{ARG1} \quad \boxed{1} \end{array} \right] \\ \textit{president} \end{array} \right] \end{array} \right\} \end{array} \right] \\ \\ \textit{nom_obj} \end{array} \right] \\ \\ \text{QSTORE} \quad \{ \} \end{array} \right]$$

The CONT values of signs that correspond to non-predicative nouns are of sort *nom_obj* (section 4.5). The INDEX value stands for the world entity described by the noun, and the RESTR value represents TOP expressions that are introduced by the noun.

(4.65) shows the sign of “*the*” that is used in (4.63). (In this thesis, “*the*” is treated semantically as “*a*”. This is of course an over-simplification.)

$$(4.65) \quad \left[\begin{array}{l} \text{PHON} \quad \langle \textit{the} \rangle \\ \\ \text{SYNSEM} \mid \text{LOC} \quad \left[\begin{array}{l} \text{CAT} \quad \left[\begin{array}{l} \text{HEAD} \quad \left[\begin{array}{l} \text{SPEC} \mid \text{LOC} \quad \left[\begin{array}{l} \text{CAT} \quad \left[\begin{array}{l} \text{HEAD} \quad \left[\begin{array}{l} \text{PRD} \quad - \\ \textit{noun} \end{array} \right] \\ \text{SPR} \quad \langle _ \rangle \\ \text{SUBJ} \quad \langle \rangle \\ \text{COMPS} \quad \langle \rangle \end{array} \right] \\ \text{CONT} \quad \boxed{2} \end{array} \right] \end{array} \right] \\ \\ \text{det} \end{array} \right] \\ \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \rangle \\ \text{COMPS} \quad \langle \rangle \end{array} \right] \\ \\ \text{CONT} \quad \left[\begin{array}{l} \text{DET} \quad \textit{exists} \\ \text{RESTIND} \quad \left[\begin{array}{l} \text{INDEX} \quad \left[\begin{array}{l} \text{TVAR} \quad + \end{array} \right] \boxed{2} \end{array} \right] \boxed{3} \end{array} \right] \\ \\ \textit{quant} \end{array} \right] \\ \\ \text{QSTORE} \quad \{ \boxed{3} \} \end{array} \right]$$

The SPEC feature of (4.65) means that “*the*” must be used as the specifier of a non-predicative \bar{N} , i.e. as the specifier of a non-predicative noun that has combined with its complements and that requires a specifier. The $\boxed{3}$ s of (4.65) cause an existential quantifier to be inserted into the quantifier store, and the $\boxed{2}$ s cause the RESTIND of that quantifier to be unified with the CONT of the \bar{N} ’s sign.

According to (4.64), “*president*” is non-predicative, it does not need to combine with any complements, and it requires a specifier. Hence, it satisfies the SPEC restrictions of (4.65), and “*the*” can be used as the specifier of “*president*”. When “*the*” combines with “*president*”, the RESTIND of (4.65) is unified with the CONT of (4.64) (because of the $\boxed{2}$ s in (4.65)), and the QSTORE of (4.65) becomes (4.66) (because of the $\boxed{3}$ s in (4.65)). The resulting noun phrase receives (4.67).

$$\begin{array}{l}
 (4.66) \quad \left\{ \begin{array}{l} \left[\begin{array}{l} \text{DET} \quad \textit{exists} \\ \text{RESTIND} \left[\begin{array}{l} \text{INDEX} \quad \textit{person_ent} \left[\begin{array}{l} \text{TVAR} \quad + \end{array} \right] \boxed{1} \\ \text{RESTR} \left\{ \begin{array}{l} \text{ET_HANDLE} \quad \textit{temp_ent} \left[\begin{array}{l} \text{TVAR} \quad + \end{array} \right] \vee \textit{now} \\ \text{MAIN_PSOA} \quad \textit{president} \left[\begin{array}{l} \text{ARG1} \quad \boxed{1} \end{array} \right] \end{array} \right\} \end{array} \right] \end{array} \right] \end{array} \right\} \\
 \left[\begin{array}{l} \text{quant} \end{array} \right] \end{array} \right\}
 \end{array}$$

$$\begin{array}{l}
 (4.67) \quad \left[\begin{array}{l} \text{PHON} \quad \langle \textit{the}, \textit{president} \rangle \\ \text{SYNSEM} \mid \text{LOC} \quad \left[\begin{array}{l} \text{CAT} \quad \left[\begin{array}{l} \text{HEAD} \quad \left[\begin{array}{l} \text{PRD} \quad - \end{array} \right] \\ \textit{noun} \end{array} \right] \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \rangle \\ \text{COMPS} \quad \langle \rangle \end{array} \right] \\ \text{CONT} \quad \left[\begin{array}{l} \text{INDEX} \quad \textit{person_ent} \left[\begin{array}{l} \text{TVAR} \quad + \end{array} \right] \boxed{1} \\ \text{RESTR} \left\{ \begin{array}{l} \text{ET_HANDLE} \quad \textit{temp_ent} \left[\begin{array}{l} \text{TVAR} \quad + \end{array} \right] \vee \textit{now} \\ \text{MAIN_PSOA} \quad \textit{president} \left[\begin{array}{l} \text{ARG1} \quad \boxed{1} \end{array} \right] \end{array} \right\} \end{array} \right] \end{array} \right] \\ \text{nom_obj} \end{array} \right] \\ \text{QSTORE} \quad \left\{ \begin{array}{l} \left[\begin{array}{l} \text{DET} \quad \textit{exists} \\ \text{RESTIND} \quad \boxed{2} \end{array} \right] \\ \text{quant} \end{array} \right\} \end{array} \right]
 \end{array}$$

According to the head feature principle (section 4.2.3), (4.67) inherits the HEAD of (4.64) (which is the sign of the “head daughter” in this case). The propagation of CONT and QSTORE is controlled by the semantics principle, which in this thesis has the simplified form of (4.68). ((4.68) uses the terminology of [Pollard & Sag 94]. I explain below what (4.68) means for readers not familiar with [Pollard & Sag 94].)

- (4.68) SEMANTICS PRINCIPLE (SIMPLIFIED VERSION OF THIS THESIS):
 In a headed phrase, (a) the QSTORE value is the union of the QSTORE values of the daughters, and (b) the SYNSEM|LOC|CONT value is token-identical with that of the semantic head. (In a headed phrase, the *semantic head* is the ADJUNCT-DAUGHTER if any, and the HEAD-DAUGHTER otherwise.)

Part (a) means that the QSTORE of each (non-lexical) syntactic constituent is the union of the QSTORES of its subconstituents. Part (b) means that each syntactic constituent inherits the CONT of its head-daughter (the noun in noun-phrases, the verb in verb phrases, the preposition in prepositional phrases), except for cases where the head-daughter combines with an adjunct-daughter (a modifier). In the latter case, the mother syntactic constituent inherits the CONT of the adjunct-daughter. (This will be discussed further in section 4.11.) Readers familiar with [Pollard & Sag 94] will have noticed that (4.68) does not allow quantifiers to be unstored from QSTORE. Apart from this, (4.68) is the same as in [Pollard & Sag 94].

(4.68) causes the QSTORE of (4.67) to become the union of the QSTORES of (4.64) (the empty set) and (4.65) (which has become (4.66)). Since “*the president*” involves no adjuncts, the “semantic head” is the “head-daughter” (i.e. “*president*”), and (4.67) inherits the CONT of (4.64) (which is now the RESTIND of (4.66)).

The “*gate 2*” of (4.63) is treated as a one-word proper name. (In the prototype NLITDB, the user has to type “*terminal 2*” as a single word; the same is true for “*J.Adams*” of (4.62). This will be discussed in section 6.6.1.) Proper names are mapped to signs whose CONT is a *nom_obj* with an empty-set RESTR.⁶ “*Gate 2*”, for example, receives (4.69).

$$(4.69) \left[\begin{array}{cc} \text{PHON} & \langle \text{gate2} \rangle \\ & \left[\begin{array}{c} \text{CAT} \left[\begin{array}{c} \text{HEAD} \left[\begin{array}{c} \text{PRD} \quad - \end{array} \right] \\ \text{noun} \end{array} \right] \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \rangle \\ \text{COMPS} \quad \langle \rangle \end{array} \right] \\ \text{CONT} \left[\begin{array}{c} \text{INDEX} \quad \text{gate2} \\ \text{RESTR} \quad \{ \} \end{array} \right] \\ \text{QSTORE} \quad \{ \} \end{array} \right] \end{array} \right]$$

⁶ In [Pollard & Sag 94], the signs of proper names involve *naming* relations, and CONTEXT and BACKGROUND features. These are not used in this thesis.

The predicative sign of “at” of (4.55), the predicative sign of “was” (which is similar to (4.57), except that it introduces a *Past*), and (4.69) cause the “was at gate 2” of (4.63) to receive (4.70).

$$(4.70) \left[\begin{array}{l} \text{PHON} \quad \langle \text{was}, \text{at}, \text{gate2} \rangle \\ \text{SYNSEM} \mid \text{LOC} \quad \left[\begin{array}{l} \text{CAT} \quad \left[\begin{array}{l} \text{HEAD} \quad \left[\begin{array}{l} \text{VFORM} \quad \text{fin} \\ \text{AUX} \quad + \end{array} \right] \\ \text{verb} \end{array} \right] \\ \text{ASPECT} \quad \text{lex_state} \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \text{NP}[-\text{PRD}] \boxed{1} \rangle \\ \text{COMPS} \quad \langle \rangle \end{array} \right] \\ \text{CONT} \quad \left[\begin{array}{l} \text{ET_HANDLE} \quad \left[\begin{array}{l} \text{TVAR} \quad + \end{array} \right] \\ \text{temp_ent} \end{array} \right] \\ \text{MAIN_PSOA} \quad \left[\begin{array}{l} \text{ARG1} \quad \boxed{1} \\ \text{ARG2} \quad \text{gate2} \end{array} \right] \\ \text{past} \quad \text{located_at} \end{array} \right] \\ \text{QSTORE} \quad \{ \} \end{array} \right]$$

When “was at gate 2” combines with “the president”, (4.63) receives (4.71). According to the semantics principle, the QSTORE of (4.71) is the union of the QSTORES of (4.70) and (4.67), and the CONT of (4.71) is the same as the CONT of (4.70).

$$(4.71) \left[\begin{array}{l} \text{PHON} \quad \langle \text{the}, \text{president}, \text{was}, \text{at}, \text{gate2} \rangle \\ \text{SYNSEM} \mid \text{LOC} \quad \left[\begin{array}{l} \text{CAT} \quad \left[\begin{array}{l} \text{HEAD} \quad \left[\begin{array}{l} \text{VFORM} \quad \text{fin} \\ \text{AUX} \quad + \end{array} \right] \\ \text{verb} \end{array} \right] \\ \text{ASPECT} \quad \text{lex_state} \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \rangle \\ \text{COMPS} \quad \langle \rangle \end{array} \right] \\ \text{CONT} \quad \left[\begin{array}{l} \text{ET_HANDLE} \quad \left[\begin{array}{l} \text{TVAR} \quad + \end{array} \right] \\ \text{temp_ent} \end{array} \right] \\ \text{MAIN_PSOA} \quad \left[\begin{array}{l} \text{ARG1} \quad \boxed{1} \\ \text{ARG2} \quad \text{gate2} \end{array} \right] \\ \text{past} \quad \text{located_at} \end{array} \right] \\ \text{QSTORE} \quad \left\{ \begin{array}{l} \text{DET} \quad \text{exists} \\ \text{RESTIND} \quad \left[\begin{array}{l} \text{INDEX} \quad \text{person_ent} \quad \left[\begin{array}{l} \text{TVAR} \quad + \end{array} \right] \boxed{1} \\ \text{RESTR} \quad \left\{ \begin{array}{l} \text{ET_HANDLE} \quad \left[\begin{array}{l} \text{TVAR} \quad + \end{array} \right] \vee \text{now} \\ \text{temp_ent} \\ \text{MAIN_PSOA} \quad \left[\begin{array}{l} \text{ARG1} \quad \boxed{1} \\ \text{president} \end{array} \right] \end{array} \right\} \end{array} \right] \\ \text{nom_obj} \quad \text{ntense} \end{array} \right\} \end{array} \right]$$

(4.72) is then extracted from (4.71), as discussed in section 4.6. Whenever an *Ntense* operator is encountered during the extraction of the TOP formulae, if there is no definite

information showing that the first argument of the *Ntense* should be *now**, the first argument is taken to be a variable. (4.71), for example, shows that the first argument of the *Ntense* could be either a TOP variable or *now**. Hence, in (4.72) the first argument of the *Ntense* has become a variable (t^v). During the post-processing phase (section 4.17 below), the *Ntense* of (4.72) would give rise to two separate formulae: one where the first argument of the *Ntense* has been replaced by *now** (current president), and one where the first argument of the *Ntense* has been replaced by the e^v of the *Past* operator (president when at gate 2). In contrast, if the sign shows that the first argument of the *Ntense* is definitely *now**, the first argument of the *Ntense* in the extracted formula is *now**, and the post-processing has no effect on this argument.

$$(4.72) \quad Ntense[t^v, president(p^v)] \wedge Past[e^v, located_at(p^v, gate2)]$$

It is possible to force a (non-predicative) noun to be interpreted as referring always to the speech time, or always to the time of the verb tense. (This also applies to the non-predicative adjectives of section 4.10 below.) To force a noun to refer always to the speech time, one sets the ET_HANDLE of the *ntense* in the noun's sign to simply *now* (instead of allowing it to be either *now* or a variable-representing index as in (4.64)). This way, the ET_HANDLE of the *ntense* in (4.71) would be *now*. (4.72) would contain *now** instead of t^v (because in this case the sign shows that the first argument of the *Ntense* should definitely be *now**), and the post-processing mechanism would have no effect.

To force a noun to refer always to the time of the verb tense, one simply omits the *Ntense* from the noun's sign. This would cause the formula extracted from the sign of (4.63) to be (4.73).

$$(4.73) \quad president(p^v) \wedge Past[e^v, located_at(p^v, gate2)]$$

The semantics of TOP's conjunction (section 3.6) and of the *Past* operator (section 3.8) require *president(p^v)* and *located_at(p^v, gate2)* to be true at the same (past) event time. Hence, (4.73) expresses the reading where the person at gate 2 was the president of that time.

There are however, two complications when (non-predicative) noun signs do not introduce *Ntenses*. (These also apply to adjective signs, to be discussed in section 4.10.) First, a past perfect sentence like (4.74) receives only (4.75), which requires

president(p^v) to be true at the event time pointed to by $e1^v$ (the “reference time”, which is required to fall within 1/1/95). That is, “*the president*” is taken to refer to somebody who was the president on 1/1/95, and who may not have been the president during the visit.

(4.74) The president had visited Rome on 1/1/95.

(4.75) $president(p^v) \wedge At[1/1/95, Past[e1^v, Perf[e2^v, visiting(p^v, rome)]]]$

In contrast, if the sign of “*president*” introduces an *Ntense*, the formula extracted from the sign of (4.74) is (4.76). The post-processing generates three different formulae from (4.76). These correspond to readings where “*president*” refers to the time of the visit (t^v replaced by $e2^v$), the reference time (t^v replaced by $e1^v$, equivalent to (4.75)), or the speech time (t^v replaced by *now**).

(4.76) $Ntense[t^v, president(p^v)] \wedge$
 $At[1/1/95, Past[e1^v, Perf[e2^v, visiting(p^v, rome)]]]$

The second complication is that (non-predicative) nouns that do not introduce *Ntenses* are taken to refer to the time of the *main clause*’s tense, even if the nouns appear in subordinate clauses (subordinate clauses will be discussed in section 4.14). For example, if “*president*” does not introduce an *Ntense*, (4.77) is mapped to (4.78). The semantics of (4.78) requires the visitor to have been president during the building of terminal 2 (the visitor is not required to have been president during the visit to terminal 3).

(4.77) Housecorp built terminal 2 before the president visited terminal 3.

(4.78) $president(p^v) \wedge Before[Past[e1^v, visiting(p^v, term3)],$
 $Past[e2^v, Culm[building(housecorp, term2)]]]$

In contrast, if “*president*” introduces an *Ntense*, the post-processing (section 4.17 below) generates three readings, where “*president*” refers to the speech time, the time of the building, or the time of the visit.

The non-predicative signs of nouns like “*day*” or “*summer*”, that refer to members of partitionings (section 3.4) are similar to the non-predicative signs of “ordinary” nouns like “*president*”, except that they introduce *Part* operators, and they do not introduce *Ntenses*. (4.79), for example, shows the non-predicative sign of “*day*”. (The *day* and *day_ent_var* sorts are as in figure 4.4 on page 126.)

$$(4.79) \left[\begin{array}{cc} \text{PHON} & \langle \text{day} \rangle \\ \text{SYNSEM} | \text{LOC} & \left[\begin{array}{c} \text{CAT} \left[\begin{array}{c} \text{HEAD} \left[\begin{array}{c} \text{PRD} \quad - \\ \text{noun} \end{array} \right] \\ \text{SPR} \quad \langle \text{LOC} | \text{CAT} | \text{HEAD} \quad \text{det} \rangle \\ \text{SUBJ} \quad \langle \rangle \\ \text{COMPS} \quad \langle \rangle \end{array} \right] \\ \text{CONT} \left[\begin{array}{c} \text{INDEX} \quad \text{day_ent_var} \boxed{1} \\ \text{RESTR} \quad \left\{ \begin{array}{c} \text{PARTNG} \quad \text{day} \\ \text{PART_VAR} \quad \boxed{1} \end{array} \right\} \end{array} \right] \\ \text{nom_obj} \end{array} \right] \\ \text{QSTORE} \quad \{ \} \end{array} \right]$$

Names of months and days (e.g. “Monday”, “January”) that can be used both with and without determiners (e.g. “on a Monday”, “on Monday”) receive two non-predicative signs each: one that requires a determiner, and one that does not. Finally, proper names that refer to particular time-periods (e.g. the year-name “1991”, the date “25/10/95”) receive non-predicative signs that are similar to those of “normal” proper names (e.g. “gate 2”), except that their INDEX values are subsorts of *temp_ent* rather than *non_temp_ent*. I demonstrate in following sections how the signs of temporal nouns and proper names (e.g. “day”, “25/10/95”) are used to form the signs of temporal adverbials (e.g. “for two days”, “before 25/10/95”).

4.9.2 Predicative nouns

I now turn to predicative nouns, like the “*president*” of (4.62). (4.80) shows the predicative sign of “*president*”. Unlike non-predicative noun-signs, whose CONT values are of sort *nom_obj*, the CONT values of predicative noun-signs are of sort *psoa*. The *president* in (4.80) is a subsort of *psoa*.

$$(4.80) \left[\begin{array}{cc} \text{PHON} & \langle \text{president} \rangle \\ \text{SYNSEM} | \text{LOC} & \left[\begin{array}{c} \text{CAT} \left[\begin{array}{c} \text{HEAD} \left[\begin{array}{c} \text{PRD} \quad + \\ \text{noun} \end{array} \right] \\ \text{SPR} \quad \langle \text{LOC} | \text{CAT} | \text{HEAD} \quad \text{det} \rangle \\ \text{SUBJ} \quad \langle \text{NP}[-\text{PRD}] \boxed{1} \rangle \\ \text{COMPS} \quad \langle \rangle \end{array} \right] \\ \text{CONT} \left[\begin{array}{c} \text{ARG1} \quad \text{person_ent} \boxed{1} \\ \text{president} \end{array} \right] \end{array} \right] \\ \text{QSTORE} \quad \{ \} \end{array} \right]$$

Unlike non-predicative nouns that do not require subjects (e.g. (4.64)), predicative nouns do require subjects. In (4.80), “*president*” requires a non-predicative noun

phrase as its subject. The $\boxed{1}$ denotes the index of that noun phrase.

In the HPSG version of this thesis, the predicative signs of nouns are generated automatically from the non-predicative ones by (4.81).⁷

(4.81) PREDICATIVE NOUNS LEXICAL RULE:

$$\begin{array}{c}
 \left[\begin{array}{c} \text{SYNSEM} \mid \text{LOC} \\ \text{CAT} \left[\begin{array}{c} \text{HEAD} \left[\begin{array}{c} \text{PRD} \quad - \\ \text{noun} \end{array} \right] \\ \text{SUBJ} \quad \langle \rangle \end{array} \right] \\ \text{CONT} \left[\begin{array}{c} \text{INDEX} \quad \boxed{1} \\ \text{RESTR} \quad \{ \boxed{2} \} \end{array} \right] \\ \text{nom_obj} \end{array} \right] \\
 \Downarrow \\
 \left[\begin{array}{c} \text{SYNSEM} \mid \text{LOC} \\ \text{CAT} \left[\begin{array}{c} \text{HEAD} \left[\begin{array}{c} \text{PRD} \quad + \\ \text{noun} \end{array} \right] \\ \text{SUBJ} \quad \langle \text{NP}[-\text{PRD}] \boxed{1} \rangle \end{array} \right] \\ \text{CONT} \quad \text{remove_ntense}(\boxed{2}) \end{array} \right]
 \end{array}$$

The *remove_ntense*($\boxed{2}$) in (4.81) means that if $\boxed{2}$ (the single element of the RESTR set of the non-predicative sign) is of sort *ntense*, then the CONT of the predicative sign should be the MAIN_PSOA of $\boxed{2}$ (see also (4.64)). Otherwise, the CONT of the predicative sign should be $\boxed{2}$. In other words, if the non-predicative sign introduces an *Ntense*, the *Ntense* is removed in the predicative sign. This is related to the observation in section 2.11, that noun phrases that are complements of “to be” always refer to the time of the verb tense. For example, (4.82) means that J.Adams was the president in 1992, not at the speech time. (4.82) is represented correctly by (4.83) which contains no *Ntenses*.

(4.82) J.Adams was the president in 1992.

(4.83) *At*[1992, *Past*[*e*^v, *president*(*j_adams*)]]

TOP predicates introduced by predicative nouns (e.g. *president*(*j_adams*) in (4.83)) end up within the operators of the tenses of “to be” (e.g. the *Past* of (4.83)). This requires the predicates to hold at the times of the tenses.

As with previous lexical rules, features not shown in (4.81) (e.g. SPR, COMPS) have the same values in both the original and the generated signs. For example, (4.81) generates (4.80) from (4.64).

⁷ Apart from the *remove_ntense*, (4.81) is essentially the same as Borsley’s “predicative NP lexical rule”, discussed in the footnote of p.360 of [Pollard & Sag 94].

In this thesis, determiners also receive different signs for their uses in predicative and non-predicative noun phrases. (Pollard and Sag do not provide much information on determiners of predicative noun phrases. The footnote of p.360 of [Pollard & Sag 94], however, seems to acknowledge that determiners of predicative noun phrases have to be treated differently from determiners of non-predicative noun phrases.) For example, apart from (4.65), “*the*” is also given (4.84). The SPEC of (4.84) shows that (4.84) can only be used with predicative nouns (cf. (4.65)). Unlike determiners of non-predicative noun phrases, determiners of predicative noun-phrases have no semantic contribution (the SYNSEM|LOC of (4.84) is simply a copy of the CONT of the noun, and no quantifier is introduced in QSTORE; cf. (4.65)).

$$(4.84) \left[\begin{array}{l} \text{PHON} \quad \langle the \rangle \\ \\ \text{SYNSEM|LOC} \\ \\ \text{QSTORE} \quad \{ \} \end{array} \left[\begin{array}{l} \text{CAT} \\ \\ \text{CONT} \quad \boxed{2} \end{array} \left[\begin{array}{l} \text{HEAD} \\ \\ \text{SPEC|LOC} \\ \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \rangle \\ \text{COMPS} \quad \langle \rangle \end{array} \left[\begin{array}{l} \text{CAT} \\ \\ \text{CONT} \quad \boxed{2} \end{array} \left[\begin{array}{l} \text{HEAD} \quad \textit{noun} \quad \left[\text{PRD} \quad + \right] \\ \text{SPR} \quad \langle - \rangle \\ \text{SUBJ} \quad \langle - \rangle \\ \text{COMPS} \quad \langle \rangle \end{array} \right] \right] \right] \right] \right]$$

In (4.62), when “*the*” combines with “*president*”, the resulting noun phrase receives (4.85). (HPSG’s principles, including the semantics principle of (4.68), cause (4.85) to inherit the HEAD, SUBJ, and CONT of (4.80).)

$$(4.85) \left[\begin{array}{l} \text{PHON} \quad \langle the, president \rangle \\ \\ \text{SYNSEM|LOC} \\ \\ \text{QSTORE} \quad \{ \} \end{array} \left[\begin{array}{l} \text{CAT} \\ \\ \text{CONT} \quad \textit{president} \end{array} \left[\begin{array}{l} \text{HEAD} \quad \textit{noun} \quad \left[\text{PRD} \quad + \right] \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \text{NP}[-\text{PRD}] \boxed{1} \rangle \\ \text{COMPS} \quad \langle \rangle \end{array} \right] \left[\begin{array}{l} \text{ARG1} \quad \textit{person_ent} \boxed{1} \end{array} \right] \right] \right]$$

Apart from (4.46) and (4.57), “*is*” also receives (4.86), which allows the complement of “*is*” to be a predicative noun phrase. (There is also a sign of “*is*” for adjectival complements, as in “*Runway 2 is closed.*”; this will be discussed in section 4.10. “*Was*”

receives similar signs.) The $\boxed{4}$ s in (4.86) denote the CONT of the predicative noun-phrase.

$$(4.86) \left[\begin{array}{ll} \text{PHON} & \langle is \rangle \\ \text{SYNSEM} | \text{LOC} & \left[\begin{array}{l} \text{CAT} \left[\begin{array}{l} \text{HEAD} \left[\begin{array}{l} \text{VFORM } fin \\ \text{AUX } + \end{array} \right] \\ \text{verb} \\ \text{ASPECT } lex_state \\ \text{SPR } \langle \rangle \\ \text{SUBJ } \langle \boxed{3} \rangle \\ \text{COMPS } \langle \text{NP}[\text{SUBJ } \langle \boxed{3} \rangle, \text{PRD } +]:\boxed{4} \rangle \end{array} \right] \\ \text{CONT}_{pres} \left[\begin{array}{l} \text{MAIN_PSOA } \boxed{4} \end{array} \right] \end{array} \right] \\ \text{QSTORE} & \{ \} \end{array} \right]$$

(4.86) and (4.85) cause the “is the president” of (4.62) to receive (4.87). Finally, when “is the president” combines with “J.Adams”, (4.62) receives a sign with an empty QSTORE, whose CONT represents (4.88).

$$(4.87) \left[\begin{array}{ll} \text{PHON} & \langle is, the, president \rangle \\ \text{SYNSEM} | \text{LOC} & \left[\begin{array}{l} \text{CAT} \left[\begin{array}{l} \text{HEAD} \left[\begin{array}{l} \text{VFORM } fin \\ \text{AUX } + \end{array} \right] \\ \text{verb} \\ \text{ASPECT } lex_state \\ \text{SPR } \langle \rangle \\ \text{SUBJ } \langle \text{NP}[-\text{PRD } \boxed{1}] \rangle \\ \text{COMPS } \langle \rangle \end{array} \right] \\ \text{CONT}_{pres} \left[\begin{array}{l} \text{MAIN_PSOA } \left[\text{ARG1 } person_ent\boxed{1} \right] \\ \text{president} \end{array} \right] \end{array} \right] \\ \text{QSTORE} & \{ \} \end{array} \right]$$

$$(4.88) \quad Pres[president(j_adams)]$$

There are currently two complications with predicative noun phrases. The first is that in the non-predicative signs of proper names like “gate2”, the value of RESTR is the empty set (see (4.69)). Hence, (4.81) does not generate the corresponding predicative signs, because the non-predicative signs do not match the RESTR description of the LHS of (4.81) (which requires the RESTR value to be a one-element set). This causes (4.89) to be rejected, because there is no predicative sign for “J.Adams”.

$$(4.89) \quad \text{The inspector is J.Adams.}$$

One way to solve this problem is to employ the additional rule of (4.90).

(4.90) ADDITIONAL PREDICATIVE NOUNS LEXICAL RULE:

$$\begin{array}{c}
 \left[\begin{array}{c} \text{SYNSEM} \mid \text{LOC} \\ \text{CAT} \left[\begin{array}{c} \text{HEAD} \left[\begin{array}{c} \text{PRD} \quad - \\ \text{noun} \end{array} \right] \\ \text{SUBJ} \quad \langle \rangle \end{array} \right] \\ \text{CONT} \left[\begin{array}{c} \text{INDEX} \quad \boxed{1} \\ \text{RESTR} \quad \{ \} \end{array} \right] \\ \text{nom_obj} \end{array} \right] \\
 \Downarrow \\
 \left[\begin{array}{c} \text{SYNSEM} \mid \text{LOC} \\ \text{CAT} \left[\begin{array}{c} \text{HEAD} \left[\begin{array}{c} \text{PRD} \quad + \\ \text{noun} \end{array} \right] \\ \text{SUBJ} \quad \langle \text{NP}[-\text{PRD}] \boxed{2} \rangle \end{array} \right] \\ \text{CONT} \left[\begin{array}{c} \text{ARG1} \quad \boxed{1} \\ \text{ARG2} \quad \boxed{2} \end{array} \right] \\ \text{identity} \end{array} \right]
 \end{array}$$

This would generate (4.91) from the non-predicative sign of “*J.Adams*” (which is similar to (4.69)). (4.86) and (4.91) would cause (4.89) to be mapped to (4.92). (I assume here that the non-predicative “*inspector*” does not introduce an *Ntense*.)

$$(4.91) \quad \left[\begin{array}{c} \text{PHON} \quad \langle J.Adams \rangle \\ \text{SYNSEM} \mid \text{LOC} \left[\begin{array}{c} \text{CAT} \left[\begin{array}{c} \text{HEAD} \left[\begin{array}{c} \text{PRD} \quad + \\ \text{noun} \end{array} \right] \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \text{NP}[-\text{PRD}] \boxed{2} \rangle \\ \text{COMPS} \quad \langle \rangle \end{array} \right] \\ \text{CONT} \left[\begin{array}{c} \text{ARG1} \quad j_adams \\ \text{ARG2} \quad \boxed{2} \end{array} \right] \\ \text{identity} \end{array} \right] \\ \text{QSTORE} \quad \{ \} \end{array} \right]$$

$$(4.92) \quad \text{inspector}(\text{insp}^v) \wedge \text{Pres}[\text{identity}(j_adams, \text{insp}^v)]$$

identity(τ_1, τ_2) is intended to be true at event times where its two arguments denote the same entity. This calls for a special domain-independent semantics for *identity*(τ_1, τ_2). I have not explored this issue any further, however, and (4.90) is not used in the prototype NLITDB.

A second complication is that the non-predicative sign of “*Monday*” (which is similar to (4.79)) and the treatment of predicative noun phrases above lead to an attempt to map (4.93) to (4.94).

$$(4.93) \quad 23/10/95 \text{ was a Monday.}$$

$$(4.94) \quad Past[e^v, Part[monday^g, 23/10/95]]$$

(4.94) is problematic for two reasons. (a) The past tense of (4.93) is in effect ignored, because the denotation of $Part[\sigma, \beta]$ does not depend on lt , which is what the $Past$ operator affects (see sections 3.6 and 3.8). Hence, the implication of (4.93) that 23/10/95 is a past day is not captured. This problem could be solved by adding the constraint $g(\beta) \sqsubseteq lt$ in the semantics of $Part[\sigma, \beta]$ (section 3.6). (b) (4.94) violates the syntax of TOP (section 3.2), which does not allow the second argument of a $Part$ operator to be a constant. This problem could be solved by modifying TOP to allow the second argument of $Part$ to be a constant.

4.10 Adjectives

Following Pollard and Sag ([Pollard & Sag 87], pp. 64 – 65), adjectives also receive different signs for their predicative and non-predicative uses. When used as complements of “to be” (e.g. “closed” in (4.95)) adjectives are said to be predicative. In all other cases (e.g. “closed” in (4.96)), adjectives are non-predicative. ((4.95) is actually ambiguous. The “closed” may be a predicative adjective, or the passive form of “to close”. As noted in section 2.13, however, passives are ignored in this thesis. Hence, I ignore the passive reading of (4.95).)

$$(4.95) \quad \text{Runway 2 was closed.}$$

$$(4.96) \quad \text{BA737 landed on a closed runway.}$$

In the airport domain, the predicative sign of the adjective “closed” is (4.97).

$$(4.97) \quad \left[\begin{array}{cc} \text{PHON} & \langle \text{closed} \rangle \\ \text{SYNSEM} \mid \text{LOC} & \left[\begin{array}{cc} \text{CAT} & \left[\begin{array}{cc} \text{HEAD} & \text{adj} \left[\begin{array}{cc} \text{PRD} & + \end{array} \right] \\ \text{SPR} & \langle \rangle \\ \text{SUBJ} & \langle \text{NP}[-\text{PRD}] \boxed{1} \rangle \\ \text{COMPS} & \langle \rangle \end{array} \right] \\ \text{CONT} & \left[\begin{array}{cc} \text{closed} & \left[\text{ARG1} \quad (\text{gate_ent} \vee \text{runway_ent}) \boxed{1} \right] \end{array} \right] \end{array} \right] \\ \text{QSTORE} & \{ \} \end{array} \right]$$

As noted in section 4.9, “is” and “was” receive four signs each. One for progressive forms (see (4.46)), one for prepositional phrase complements (see (4.57)), one for noun-

phrase complements (see (4.86)), and one for adjectival complements ((4.98) below).

(4.98) and (4.97) cause (4.95) to be mapped to (4.99).

$$(4.98) \quad \left[\begin{array}{l} \text{PHON} \quad \langle was \rangle \\ \\ \text{SYNSEM} | \text{LOC} \\ \\ \text{QSTORE} \quad \{ \} \end{array} \left[\begin{array}{l} \text{CAT} \left[\begin{array}{l} \text{HEAD} \left[\begin{array}{l} \text{VFORM} \quad fin \\ \text{AUX} \quad + \end{array} \right] \\ \text{ASPECT} \quad lex_state \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle [3] \rangle \\ \text{COMPS} \quad \langle \text{LOC} \left[\begin{array}{l} \text{CAT} \left[\begin{array}{l} \text{HEAD} \quad adj \left[\begin{array}{l} \text{PRD} \quad + \end{array} \right] \\ \text{SUBJ} \quad \langle [3] \rangle \\ \text{COMPS} \quad \langle \rangle \end{array} \right] \\ \text{CONT} \quad [2] \end{array} \right] \rangle \rangle \rangle \rangle \\ \text{CONT} \left[\begin{array}{l} \text{ET_HANDLE} \quad temp_ent \left[\begin{array}{l} \text{TVAR} \quad + \end{array} \right] \\ \text{MAIN_PSOA} \quad [2] \end{array} \right] \\ \text{past} \end{array} \right] \end{array} \right]$$

$$(4.99) \quad Past[e^v, closed(runway2)]$$

(4.100) shows the non-predicative sign of “closed”. The “closed” in (4.96) is a modifier (adjunct) of “runway”. The MOD in (4.100) refers to the SYNSEM of the sign of the noun that the adjective modifies. The SYNSEM|LOC|CONT of (4.100) is the same as the one of the noun-sign, except that an *Ntense* is added to the RESTR of the noun-sign (i.e. to the set denoted by [2]). The additional *Ntense* requires the entity described by the noun (the entity represented by [1]) to be closed at some unspecified time. The INDEX of the noun’s sign is also required to represent a gate or runway.

$$(4.100) \quad \left[\begin{array}{l} \text{PHON} \quad \langle \text{closed} \rangle \\ \text{SYNSEM} \mid \text{LOC} \\ \text{QSTORE} \quad \{ \} \end{array} \right] \left[\begin{array}{l} \text{CAT} \\ \text{CONT} \end{array} \right] \left[\begin{array}{l} \text{HEAD} \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \rangle \\ \text{COMPS} \quad \langle \rangle \\ \text{INDEX} \quad (\text{gate_ent} \vee \text{runway_ent}) \boxed{1} \\ \text{RESTR} \quad \boxed{2} \cup \left\{ \begin{array}{l} \text{ET_HANDLE} \quad \left[\begin{array}{l} \text{TVAR} \quad + \vee \text{now} \end{array} \right] \\ \text{MAIN_PSOA} \quad \left[\begin{array}{l} \text{ARG1} \quad \boxed{1} \end{array} \right] \end{array} \right\} \end{array} \right] \left[\begin{array}{l} \text{PRD} \quad - \\ \text{MOD} \mid \text{LOC} \\ \text{nom_obj} \end{array} \right] \left[\begin{array}{l} \text{CAT} \quad \left[\begin{array}{l} \text{HEAD} \quad \text{noun} \\ \text{SPR} \quad \langle - \rangle \\ \text{COMPS} \quad \langle \rangle \end{array} \right] \\ \text{CONT} \quad \left[\begin{array}{l} \text{INDEX} \quad \boxed{1} \\ \text{RESTR} \quad \boxed{2} \end{array} \right] \end{array} \right] \right]$$

In the airport domain, the non-predicative sign of “runway” is (4.101). (I assume that “runway” does not introduce an *Ntense*.)

$$(4.101) \quad \left[\begin{array}{l} \text{PHON} \quad \langle \text{runway} \rangle \\ \text{SYNSEM} \mid \text{LOC} \\ \text{QSTORE} \quad \{ \} \end{array} \right] \left[\begin{array}{l} \text{CAT} \\ \text{CONT} \end{array} \right] \left[\begin{array}{l} \text{HEAD} \quad \left[\begin{array}{l} \text{PRD} \quad - \\ \text{noun} \end{array} \right] \\ \text{SPR} \quad \langle \text{LOC} \mid \text{CAT} \mid \text{HEAD} \quad \text{det} \rangle \\ \text{SUBJ} \quad \langle \rangle \\ \text{COMPS} \quad \langle \rangle \\ \text{INDEX} \quad \text{runway_ent} \boxed{1} \\ \text{RESTR} \quad \left\{ \text{runway} \quad \left[\begin{array}{l} \text{ARG1} \quad \boxed{1} \end{array} \right] \right\} \end{array} \right]$$

In (4.96), “closed” combines with “runway” according to HPSG’s head-adjunct schema (see [Pollard & Sag 94]). “Closed runway” receives the sign of (4.102), where $\boxed{3}$ is the set of (4.103). (Sets of *psaos* are treated as conjunctions.)

$$(4.102) \quad \left[\begin{array}{l} \text{PHON} \quad \langle \text{closed}, \text{runway} \rangle \\ \\ \text{SYNSEM} \mid \text{LOC} \\ \\ \text{QSTORE} \quad \{ \} \end{array} \left[\begin{array}{l} \text{CAT} \left[\begin{array}{l} \text{HEAD} \quad \text{noun} \left[\text{PRD} \quad - \right] \\ \text{SPR} \quad \langle \text{LOC} \mid \text{CAT} \mid \text{HEAD} \quad \text{det} \rangle \\ \text{SUBJ} \quad \langle \rangle \\ \text{COMPS} \quad \langle \rangle \end{array} \right] \\ \text{CONT} \left[\begin{array}{l} \text{INDEX} \quad \text{runway_ent} \boxed{1} \\ \text{RESTR} \quad \boxed{3} \end{array} \right] \\ \text{nom_obj} \end{array} \right] \right]$$

$$(4.103) \quad \left\{ \begin{array}{l} \text{runway} \left[\text{ARG1} \quad \boxed{1} \right], \\ \text{ntense} \left[\begin{array}{l} \text{ET_HANDLE} \quad \text{temp_ent} \left[\text{TVAR} \quad + \right] \vee \text{now} \\ \text{MAIN_PSOA} \quad \text{closed} \left[\text{ARG1} \quad \boxed{1} \right] \end{array} \right] \end{array} \right\} \boxed{3}$$

The principles of HPSG cause (4.102) to inherit the HEAD and SPR of (4.101). (4.102) inherits the CONT of (4.100) according to the semantics principle of (4.68) (in this case, the “semantic head” is the adjunct “closed”). (4.102), the sign of “landed” (which is the same as (4.1), except that it also introduces *Past* and *Culm* operators), and the non-predicative sign of “on” (which is similar to (4.59)), cause (4.96) to be mapped to the (4.104). During the post-processing (section 4.17 below), (4.104) gives rise to two different formulae, one where t^v is replaced by now^* (currently closed runway), and one where t^v is replaced by e^v (closed during the landing).

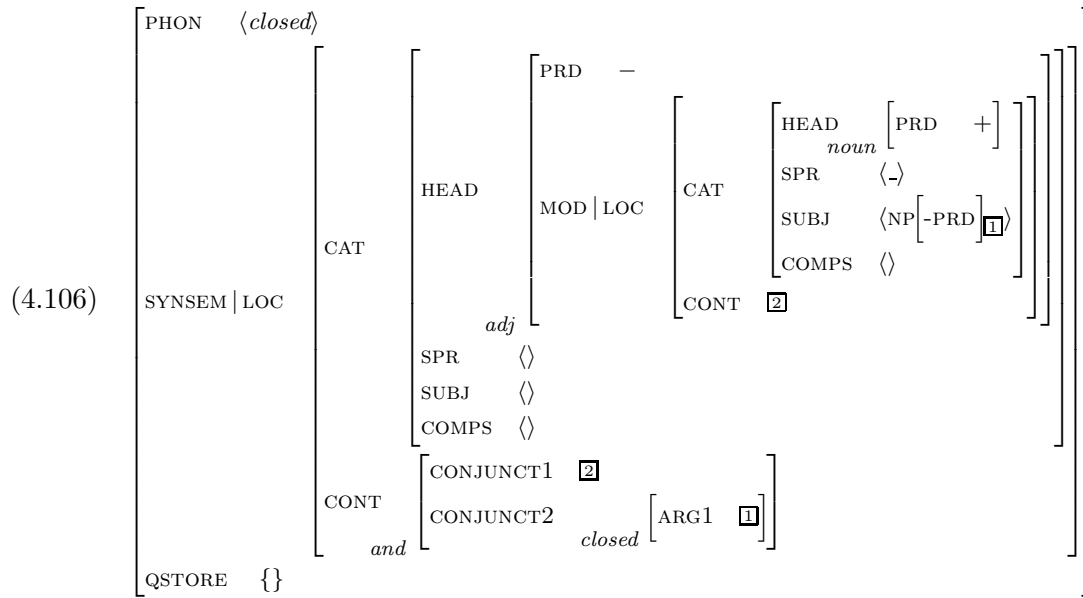
$$(4.104) \quad \text{runway}(r^v) \wedge \text{Ntense}[t^v, \text{closed}(r^v)] \wedge \text{Past}[e^v, \text{Culm}[\text{landing_on}(\text{occr}^v, \text{ba737}, r^v)]]$$

An additional sign is needed for each non-predicative adjective to allow sentences like (4.105), where a non-predicative adjective (“closed”) combines with a predicative noun (“runway”).

$$(4.105) \quad \text{Runway 2 is a closed runway.}$$

(4.100) cannot be used in (4.105), because here “runway” is predicative, and hence the CONT of its sign is a *psoa* (the predicative sign of “runway” is similar to (4.80)). In contrast, (4.100) assumes that the CONT of the noun is a *nom_obj*. One has to use the additional sign of (4.106).⁸ Using (4.106), (4.105) is mapped to (4.107), which requires runway 2 to be closed at the speech time.

⁸ It is unclear how (4.106) could be written in the HPSG version of [Pollard & Sag 94]. In [Pollard & Sag 94], the *and* sort does not exist, and conjunctions of *psoas* can only be expressed using sets of *psoas*, as in (4.103). In (4.106), however, the value of $\text{SYNSEM}[\text{LOC}|\text{CONT}]$ cannot be a set of *psoas*, because CONT accepts only values whose sort is *psoa*, *nom_obj*, or *quant*.



$$(4.110) \left[\begin{array}{l} \text{PHON} \quad \langle at \rangle \\ \\ \text{SYNSEM} | \text{LOC} \\ \\ \text{QSTORE} \quad \{ \} \end{array} \left[\begin{array}{l} \text{CAT} \\ \\ \text{CONT} \quad \begin{array}{l} at_op \\ \end{array} \end{array} \left[\begin{array}{l} \text{HEAD} \quad \begin{array}{l} \text{PRD} \quad - \\ \text{MOD} \quad S[VFORM \textit{fin}]:\boxed{2} \vee VP[VFORM \textit{psp}]:\boxed{2} \\ \text{MOD} | \text{LOC} | \text{CAT} | \text{ASPECT} \quad \begin{array}{l} state \vee activity \\ \vee point \end{array} \end{array} \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \rangle \\ \text{COMPS} \quad \langle NP[-PRD]_{minute_ent}\boxed{1} \rangle \\ \text{ASPECT} \quad point \\ \text{TIME_SPEC} \quad \boxed{1} \\ \text{MAIN_PSOA} \quad \boxed{2} \end{array} \right] \right] \right]$$

The MOD feature refers to the SYNSEM of the sign of the constituent modified by “at”. $S[VFORM \textit{fin}]:\boxed{2}$ is an abbreviation for a finite sentence (a finite verb form that has combined with its subject and complements). The $\boxed{2}$ refers to the CONT of the sign of the finite sentence. Similarly, $VP[VFORM \textit{psp}]:\boxed{2}$ stands for a past participle verb phrase (a past participle that has combined with its complements but not its subject). The MOD of (4.110) means that (4.110) can be used when “at” modifies finite sentences or past participle verb phrases, whose aspect is state, activity, or point. Generally, in this thesis temporal adverbials (punctual adverbials, period adverbials, duration adverbials) and temporal subordinate clauses (to be discussed in section 4.14) are allowed to modify only finite sentences and past participle verb phrases.

(4.110) and the sign of “5:00pm” (shown in (4.111)) cause “at 5:00pm” to receive (4.112) (“5:00pm” acts as the noun-phrase complement of “at”).

$$(4.111) \left[\begin{array}{l} \text{PHON} \quad \langle 5:00pm \rangle \\ \\ \text{SYNSEM} | \text{LOC} \\ \\ \text{QSTORE} \quad \left\{ \left[\begin{array}{l} \text{DET} \quad exists \\ \text{RESTIND} \quad \boxed{3} \end{array} \right] \right\} \end{array} \left[\begin{array}{l} \text{CAT} \\ \\ \text{CONT} \quad \begin{array}{l} nom_obj \\ \end{array} \end{array} \left[\begin{array}{l} \text{HEAD} \quad \begin{array}{l} noun \\ \text{PRD} \quad - \end{array} \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \rangle \\ \text{COMPS} \quad \langle \rangle \\ \text{INDEX} \quad minute_ent_var\boxed{1} \\ \text{RESTR} \quad \left\{ \begin{array}{l} \text{PARTNG} \quad 5:00pm \\ \text{PART_VAR} \quad \boxed{1} \end{array} \right\} \boxed{2} \end{array} \right] \right] \right]$$

$$(4.112) \quad \left[\begin{array}{l} \text{PHON} \quad \langle at, 5:00pm \rangle \\ \\ \text{SYNSEM} | \text{LOC} \\ \\ \text{QSTORE} \left\{ \begin{array}{l} \text{DET} \quad exists \\ \text{RESTIND} \left[\begin{array}{l} \text{INDEX} \quad minute_ent_var \boxed{1} \\ \text{RESTR} \left\{ \begin{array}{l} \text{PARTNG} \quad 5:00pm \\ \text{PART_VAR} \quad \boxed{1} \end{array} \right\} \end{array} \right] \end{array} \right\} \end{array} \right] \left[\begin{array}{l} \text{CAT} \\ \\ \text{CONT} \quad at_op \end{array} \right] \left[\begin{array}{l} \text{HEAD} \quad prep \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \rangle \\ \text{COMPS} \quad \langle \rangle \\ \text{ASPECT} \quad point \\ \left[\begin{array}{l} \text{TIME_SPEC} \quad \boxed{1} \\ \text{MAIN_PSOA} \quad \boxed{2} \end{array} \right] \end{array} \right] \left[\begin{array}{l} \text{PRD} \quad - \\ \text{MOD} \quad S[VFORM \textit{fin}]:\boxed{2} \vee VP[VFORM \textit{psp}]:\boxed{2} \\ \text{MOD} | \text{LOC} | \text{CAT} | \text{ASPECT} \quad state \vee activity \\ \vee point \end{array} \right] \end{array} \right]$$

According to HPSG’s head feature principle (section 4.2.3), (4.112) inherits the HEAD of (4.110) (“at” is the “head-daughter” of “at 5:00pm”, and “5:00pm” is the “complement-daughter”). Following the semantics principle of (4.68), the QSTORE of (4.112) is the union of the QSTORES of (4.110) and (4.111), and the CONT of (4.112) is the same as the CONT of (4.110) (in this case, the “semantic head” is the head-daughter, i.e. “at”).

The propagation of ASPECT is controlled by (4.113), a new principle of this thesis. (As with (4.68), in (4.113) I use the terminology of [Pollard & Sag 94].)

(4.113) ASPECT PRINCIPLE:

In a headed-phrase, the SYNSEM|LOC|CAT|ASPECT value is token-identical with that of the semantic head. (In a headed phrase, the *semantic head* is the ADJUNCT-DAUGHTER if any, and the HEAD-DAUGHTER otherwise.)

(4.113) means that each syntactic constituent inherits the ASPECT of its head-daughter (the noun in noun phrases, the verb in verb phrases, the preposition in prepositional phrases), except for cases where the head-daughter combines with an adjunct-daughter (a modifier). In the latter case, the mother syntactic constituent inherits the CONT of the adjunct-daughter. (4.113) causes (4.112) to inherit the ASPECT value of the semantic head “at”.

The “*tank 2 was empty*” of (4.109) receives (4.114).

$$(4.114) \left[\begin{array}{l} \text{PHON} \quad \langle \text{tank2}, \text{was}, \text{empty} \rangle \\ \\ \text{SYNSEM} \mid \text{LOC} \quad \left[\begin{array}{l} \text{CAT} \quad \left[\begin{array}{l} \text{HEAD} \quad \left[\begin{array}{l} \text{VFORM} \quad \text{fin} \\ \text{AUX} \quad + \end{array} \right] \\ \text{verb} \\ \text{ASPECT} \quad \text{lex_state} \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \rangle \\ \text{COMPS} \quad \langle \rangle \end{array} \right] \\ \\ \text{CONT} \quad \left[\begin{array}{l} \text{ET_HANDLE} \quad \left[\begin{array}{l} \text{TVAR} \quad + \end{array} \right] \\ \text{temp_ent} \\ \text{MAIN_PSOA} \quad \left[\begin{array}{l} \text{ARG1} \quad \text{tank2} \end{array} \right] \\ \text{empty} \end{array} \right] \\ \text{past} \end{array} \right] \\ \\ \text{QSTORE} \quad \{ \} \end{array} \right]$$

When “*tank 2 was empty*” combines with “*at 5:00pm*”, (4.109) receives (4.115). In this case, “*tank 2 was empty*” is the head-daughter, and “*at 5:00pm*” is an adjunct-daughter (a modifier). Hence, according to (4.113), (4.115) inherits the ASPECT of (4.112) (i.e. *point*; in contrast, the ASPECT of (4.114) was *lex_state*.) This is in accordance with the arrangements of section 2.9.1, whereby punctual adverbials trigger an aspectual shift to *point*.

$$(4.115) \left[\begin{array}{l} \text{PHON} \quad \langle \text{tank2}, \text{was}, \text{empty}, \text{at}, 5:00\text{pm} \rangle \\ \\ \text{SYNSEM} \mid \text{LOC} \quad \left[\begin{array}{l} \text{CAT} \quad \left[\begin{array}{l} \text{HEAD} \quad \left[\begin{array}{l} \text{VFORM} \quad \text{fin} \\ \text{AUX} \quad + \end{array} \right] \\ \text{verb} \\ \text{ASPECT} \quad \text{point} \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \rangle \\ \text{COMPS} \quad \langle \rangle \end{array} \right] \\ \\ \text{CONT} \quad \left[\begin{array}{l} \text{TIME_SPEC} \quad \boxed{1} \\ \text{MAIN_PSOA} \quad \left[\begin{array}{l} \text{ET_HANDLE} \quad \left[\begin{array}{l} \text{TVAR} \quad + \end{array} \right] \\ \text{temp_ent} \\ \text{MAIN_PSOA} \quad \left[\begin{array}{l} \text{ARG1} \quad \text{tank2} \end{array} \right] \\ \text{empty} \end{array} \right] \\ \text{at_op} \quad \text{past} \end{array} \right] \end{array} \right] \\ \\ \text{QSTORE} \quad \left\{ \left[\begin{array}{l} \text{DET} \quad \text{exists} \\ \\ \text{RESTIND} \quad \left[\begin{array}{l} \text{INDEX} \quad \text{minute_ent_var} \boxed{1} \\ \text{RESTR} \quad \left\{ \begin{array}{l} \text{PARTNG} \quad 5:00\text{pm} \\ \text{PART_VAR} \quad \boxed{1} \end{array} \right\} \\ \text{part} \end{array} \right] \end{array} \right] \right\} \right\}$$

According to the semantics principle, (4.115) also inherits the CONT of (4.112) (the sign of the modifier), and the QSTORE of (4.115) is the union of the QSTORES of (4.112) and (4.114). Finally, according to the head feature principle (section 4.2.3), (4.115) inherits the HEAD of (4.114) (the sign of the head-daughter). The QSTORE and CONT

of (4.115) represent (4.116).

$$(4.116) \quad Part[5:00pm^g, fv^v] \wedge At[fv^v, Past[e^v, empty(tank2)]]$$

The reader may wonder why temporal adverbials (e.g. “at 5:00pm” in (4.109)) are taken to modify whole finite sentences (“tank 2 was empty”), rather than finite verb phrases (“was empty”). The latter approach leads to problems in questions like “Was tank 2 empty at 5:00pm?”, where “was” combines in one step with both its subject “tank 2” and its complement “empty”, following the head-subject-complement schema of [Pollard & Sag 94]. In this case, there is no verb phrase constituent (verb that has combined with its complements but not its subject) to be modified by “at 5:00pm”.

Apart from finite sentences, temporal adverbials are also allowed to modify past participle verb phrases (see the MOD of (4.110)). This is needed in past perfect sentences like (4.117).

$$(4.117) \quad BA737 \text{ had entered sector 2 at 5:00pm.}$$

As discussed in section 2.5.5, (4.117) has two readings: one where the entrance occurs at 5:00pm, and one where 5:00pm is a “reference time”, a time where the entrance has already occurred. The two readings are expressed by (4.119) and (4.121) respectively (see also section 3.15). (4.117) is taken to be syntactically ambiguous with two possible parses, sketched in (4.118) and (4.120). These give rise to (4.119) and (4.121) respectively.

$$(4.118) \quad BA737 \text{ had } [[\text{entered sector 2}] \text{ at 5:00pm}].$$

$$(4.119) \quad Part[5:00pm^g, fv^v] \wedge Past[e1^v, Perf[e2^v, At[fv^v, enter(ba737, sector2)]]]$$

$$(4.120) \quad [BA737 \text{ had } [\text{entered sector 2}]] \text{ at 5:00pm.}$$

$$(4.121) \quad Part[5:00pm^g, fv^v] \wedge At[fv^v, Past[e1^v, Perf[e2^v, enter(ba737, sector2)]]]$$

One complication of this approach is that it generates two equivalent formulae for the present perfect (4.122), shown in (4.124) and (4.126). (“Has” does not introduce a *Perf*; see (4.37).) These correspond to the parses of (4.123) and (4.125) respectively.

$$(4.122) \quad BA737 \text{ has entered sector 2 at 5:00pm.}$$

$$(4.123) \quad [BA737 \text{ has } [\text{entered sector 2}]] \text{ at 5:00pm.}$$

$$(4.124) \quad Part[5:00pm^g, fv^v] \wedge At[fv^v, Past[e^v, enter(ba737, sector2)]]$$

(4.125) BA737 has [[entered sector 2] at 5:00pm].

(4.126) $Part[5:00pm^g, fv^v] \wedge Past[e^v, At[fv^v, enter(ba737, sector2)]]$

In the prototype NLITDB, the sign of “has” is slightly more complex than (4.37). It requires the CONT of the verb-phrase complement of “has” to be of sort *predicate*. This blocks (4.125) and (4.126), because in (4.125) the “at 5:00pm” causes the CONT of “entered sector 2 at 5:00pm” to become of sort *at_op* (it inserts an *At* operator), which is not a subsort of *predicate*.

(4.110) corresponds to the interjacent meaning of punctual adverbials, which according to table 2.2 on page 44 is possible only with states and activities. (4.110) also covers cases where punctual adverbials combine with points. There are also other “at” signs, that are similar to (4.110) but that introduce additional *Begin* or *End* operators. These correspond to the inchoative (with activities and culminating activities) and terminal (with culminating activities) meanings of punctual adverbials.

4.11.2 Period adverbials

I now turn to period adverbials (section 2.9.2). (4.127) shows one of the signs of “on” that are used when “on” introduces period adverbials.

(4.127)
$$\left[\begin{array}{l} \text{PHON} \quad \langle on \rangle \\ \\ \text{SYNSEM} \mid \text{LOC} \\ \\ \text{QSTORE} \quad \{ \} \end{array} \left[\begin{array}{l} \text{CAT} \\ \\ \text{CONT} \end{array} \left[\begin{array}{l} \text{HEAD} \left[\begin{array}{l} \text{PRD} \quad - \\ \text{MOD} \quad S[VFORM \textit{fin}]:[2] \vee VP[VFORM \textit{psp}]:[2] \\ \text{MOD} \mid \text{LOC} \mid \text{CAT} \mid \text{ASPECT} \quad \textit{culmact} \end{array} \right] \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \rangle \\ \text{COMPS} \quad \langle NP[-PRD]_{day_ent}[1] \rangle \\ \text{ASPECT} \quad \textit{point} \\ \text{TIME_SPEC} \quad [1] \\ \text{MAIN_PSOA} \quad \left[\begin{array}{l} \text{MAIN_PSOA} \quad [2] \\ \textit{end} \end{array} \right] \end{array} \right] \right] \right]$$

(4.127), which can be used only when the “on ... ” adverbial modifies a culminating activity, corresponds to the reading where the situation of the culminating activity simply reaches its completion within the adverbial’s period (table 2.3 on page 49). ((4.127) causes the aspectual class of the culminating activity to become point. This

agrees with table 2.3.) For example, (4.127) causes (4.128) to be mapped to (4.129). (I assume here that “to repair” is classified as culminating activity verb.) Intuitively, (4.129) requires a past period e^v to exist, such that e^v covers a whole repair of engine 2 by J.Adams (from start to completion), and the end-point of e^v falls within some Monday. That is, the repair must have been completed on Monday, but it may have started before Monday.

(4.128) J.Adams repaired engine 2 on Monday.

(4.129) $Part[monday^g, m^v] \wedge$
 $At[m^v, End[Past[e^v, [Culm[repairing(occr^v, j_adams, eng2)]]]]]$

There is also an “on” sign that is similar to (4.127), but that does not introduce an *End* operator, preserves the ASPECT of the modified expression, and can be used when “on . . . ” adverbials modify expressions from all four aspectual classes. This sign causes (4.128) to be mapped to (4.130) (the prototype NLITDB would generate both (4.129) and (4.130)). (4.130) corresponds to the reading where the repair must have both started and been completed within a (the same) Monday. The “on” sign that does not introduce an *End* also gives rise to appropriate formulae when “on . . . ” adverbials modify state, activity, or point expressions.

(4.130) $Part[monday^g, m^v] \wedge$
 $At[m^v, Past[e^v, [Culm[repairing(occr^v, j_adams, eng2)]]]]]$

Both (4.127) and the “on” sign that does not introduce an *End* require the noun-phrase complement of “on” to introduce an index of sort *day_ent*. The signs of “1/1/91” and “Monday” introduce indices of sorts *1/1/91* and *day_ent_var* respectively, which are subsorts of *day_ent* (see figure 4.4 on page 126). Hence, “1/1/91” and “Monday” are legitimate complements of “on” in period adverbials. In contrast, “5:00pm” introduces an index of sort *minute_ent_var* (see (4.111)), which is not a subsort of *day_ent*. Hence, (4.131) is correctly rejected.

(4.131) *Tank 2 was empty on 5:00pm.

The signs of other prepositions that introduce period adverbials (e.g. “in 1991”, “before 29/10/95”, “after 5:00pm”) and the signs of “yesterday” and “today” are similar to the signs of “on”, except that “before” and “after” introduce *Before* and *After* operators instead of *Ats*. Also, “before” is given only one sign, that does not introduce an

End (there is no “before” sign for culminating activities analogous to (4.127), that introduces an *End*). This is related to comments in section 2.9.2 that in the case of “before ... ” adverbials, requiring the situation of a culminating activity to simply reach its completion before some time (reading with *End*) is equivalent to requiring the situation to both start and reach its completion before that time (reading without *End*).

4.11.3 Duration adverbials

The treatment of “for ... ” duration adverbials is rather ad hoc from a syntax point of view. In an adverbial like “for two days”, both “two” and “days” are taken to be complements of “for”, instead of treating “two” as the determiner of “days”, and “two days” as a noun-phrase complement of “for”.

Number-words like “one”, “two”, “three”, etc. are mapped to signs of the form of (4.132). Their RESTRs are empty, and their indices represent the corresponding numbers. (The 2 of (4.132) is a subsort of *sem_num*; see section 4.4.)

$$(4.132) \left[\begin{array}{cc} \text{PHON} & \langle two \rangle \\ & \\ & \left[\begin{array}{cc} \text{CAT} & \left[\begin{array}{cc} \text{HEAD} & \left[\begin{array}{cc} \text{SPEC} & none \end{array} \end{array} \right] \\ \text{SPR} & \langle \rangle \\ \text{SUBJ} & \langle \rangle \\ \text{COMPS} & \langle \rangle \end{array} \right] \\ \text{SYNSEM | LOC} & \\ & \left[\begin{array}{cc} \text{CONT} & \left[\begin{array}{cc} \text{INDEX} & 2 \\ \text{RESTR} & \{ \} \end{array} \right] \\ nom_obj & \end{array} \right] \end{array} \right] \\ \text{QSTORE} & \{ \} \end{array} \right]$$

Although words like “one”, “two”, “three”, etc. are classified as determiners (the HEAD of (4.132) is of sort *det*), the *none* value of their SPEC does not allow them to be used as determiners of any noun. (Determiners combining with nouns are the specifiers of the nouns. The *none* means that the word of the sign cannot be the specifier of any constituent, and hence cannot be used as the determiner of any noun.)

(4.133) shows the sign of “for” that is used in duration adverbials (for typesetting reasons, I show the feature structures that correspond to [5](#) and [6](#) separately, in (4.134) and (4.135) respectively).

$$(4.133) \left[\begin{array}{c} \text{PHON} \quad \langle \text{for} \rangle \\ \\ \text{SYNSEM} \mid \text{LOC} \\ \\ \text{QSTORE} \quad \{ \} \end{array} \left[\begin{array}{c} \text{CAT} \\ \\ \text{CONT} \end{array} \left[\begin{array}{c} \text{HEAD} \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \rangle \\ \text{COMPS} \quad \langle \boxed{5}, \boxed{6} \rangle \\ \text{ASPECT} \quad \boxed{1} \\ \text{DUR_UNIT} \quad \boxed{2} \\ \text{DURATION} \quad \boxed{3} \\ \text{MAIN_PSOA} \quad \boxed{4} \end{array} \right] \right] \left[\begin{array}{c} \text{PRD} \quad - \\ \text{MOD} \quad \text{S} \left[\text{VFORM} \text{ fin} \right] : \boxed{4} \vee \text{VP} \left[\text{VFORM} \text{ psp} \right] : \boxed{4} \\ \text{MOD} \mid \text{LOC} \mid \text{CAT} \mid \text{ASPECT} \quad (\text{lex_state} \\ \vee \text{progressive} \\ \vee \text{activity}) \boxed{1} \end{array} \right] \right]$$

$$(4.134) \left[\begin{array}{c} \text{LOC} \end{array} \left[\begin{array}{c} \text{CAT} \mid \text{HEAD} \quad \text{det} \\ \text{CONT} \mid \text{INDEX} \quad \text{sem_num} \boxed{3} \end{array} \right] \boxed{5}$$

$$(4.135) \left[\begin{array}{c} \text{LOC} \end{array} \left[\begin{array}{c} \text{CAT} \\ \text{CONT} \mid \text{RESTR} \quad \left\{ \begin{array}{c} \text{part} \left[\text{PARTNG} \quad \text{compl_partng} \boxed{2} \end{array} \right] \end{array} \right\} \right] \right] \boxed{6}$$

The COMPS of (4.133) means that “for” requires two complements: a determiner that introduces a number-denoting (*sem_num*) index (like the “two” of (4.132)), and a noun that introduces a *Part* operator whose first argument is a complete partitioning name (like the “day” of (4.79)). In (4.136), “for two days” receives (4.137). (As already mentioned, no number-agreement checks are made, and plural nouns are treated semantically as singular ones. Apart from PHON, the sign of “days” is the same as (4.79).)

(4.136) Tank 2 was empty for two days.

In that case, the “for ... ” adverbial modifies a consequent state, because the “had” has caused the aspectual class of “BA737 *had circled*” to become consequent state. By not allowing “for ... ” adverbials to modify consequent states, (4.142) is blocked. This is needed, because in (4.142) two hours is the duration of a period (pointed to by $e1^v$) that follows a period (pointed to by $e2^v$) where BA737 was circling. This reading is never possible when “for ... ” adverbials are used in past perfect sentences. The “for ... ” adverbial of (4.140) can only specify the duration of the circling (a reading captured by (4.141)). (A similar observation is made on p. 587 of [Kamp & Reyle 93].)

The present treatment of “for ... ” duration adverbials causes (4.143) to receive (4.144). (4.144) does not capture correctly the meaning of (4.143), because it requires the taxiing to have been completed, i.e. BA737 to have reached gate 2. In contrast, as discussed in section 2.9.3, the “for ... ” adverbial of (4.143) cancels the normal implication of “BA737 *taxied to gate 2*.” that the taxiing was completed. The post-processing (section 4.17 below) removes the *Culm* of (4.144), generating a formula that does not require the taxiing to have been completed.

(4.143) BA737 taxied to gate 2 for five minutes.

(4.144) $For[minute^c, 5, Past[e^v, Culm[taxiing_to(ba737, gate2)]]]$

Duration adverbials introduced by “in” (e.g. (4.145)) are treated by mapping “in” to a sign that is the same as (4.133), except that it allows the adverbial to modify only culminating activities. (The framework of this thesis does not allow “in ... ” duration adverbials to modify states, activities, or points; see section 2.9.4.)

(4.145) BA737 taxied to gate 2 in five minutes.

This causes (4.145) to be mapped to (4.144), which correctly requires the taxiing to have been completed, and the duration of the taxiing (from start to completion) to be five minutes. (In this case, the post-processing does not remove the *Culm*.)

4.12 Temporal complements of habituals

Let us now examine more closely the status of temporal prepositional-phrases, like “at 5:00pm” and “on Monday” in (4.146) – (4.149).

(4.146) BA737 departed at 5:00pm.

- (4.147) BA737 departs at 5:00pm.
 (4.148) J.Adams inspected gate 2 on Monday.
 (4.149) J.Adams inspects gate 2 on Monday.

(4.146) has both a habitual and a non-habitual reading. Under the non-habitual reading, it refers to an actual departure that took place at 5:00pm. Under the habitual reading, it means that BA737 had the habit of departing at 5:00pm (this reading is easier to accept if an adverbial like “*in 1992*” is added). In (4.147), only the habitual reading is possible, i.e. BA737 currently has the habit of departing at 5:00pm. (A scheduled-to-happen reading is also possible, but as discussed in section 2.5.1 this is ignored in this thesis.) Similar comments apply to (4.148) and (4.149).

To account for the habitual and non-habitual readings of “*to depart*” in (4.146) and (4.147), the base form of “*to depart*” is given the signs of (4.150) and (4.151). These correspond to what chapter 2 called informally the habitual and non-habitual homonyms of “*to depart*”. (4.150) classifies the habitual homonym as (lexical) state, while (4.151) classifies the non-habitual homonym as point (this agrees with table 2.1 on page 26). According to (4.150), the habitual homonym requires an “*at ...*” prepositional phrase that specifies the habitual departure time (this is discussed further below). In contrast, the non-habitual homonym of (4.151) requires no complement.

(4.150)

PHON	$\langle depart \rangle$		
SYNSEM	LOC	CAT	$\left[\begin{array}{ll} \text{HEAD} & \left[\begin{array}{ll} \text{VFORM} & bse \\ \text{AUX} & - \end{array} \right] \\ & verb \\ \text{ASPECT} & lex_state \\ \text{SPR} & \langle \rangle \\ \text{SUBJ} & \langle \text{NP}[-\text{PRD}]_{flight_ent[1]} \rangle \\ \text{COMPS} & \langle \text{PP}[-\text{PRD}, \text{PFORM } at]_{minute_gappy[2]} \rangle \end{array} \right]$
		CONT	$\left[\begin{array}{ll} \text{ARG1} & [1] \\ \text{ARG2} & [2] \end{array} \right]$
QSTORE	{ }		<i>hab_departs_at</i>

$$(4.151) \left[\begin{array}{cc} \text{PHON} & \langle \text{depart} \rangle \\ \text{SYNSEM} & \left[\begin{array}{c} \text{LOC} \left[\begin{array}{c} \text{CAT} \left[\begin{array}{c} \text{HEAD} \left[\begin{array}{c} \text{VFORM} \quad bse \\ \text{AUX} \quad - \end{array} \right] \\ \text{verb} \end{array} \right] \\ \text{ASPECT} \quad point \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \text{NP}[-\text{PRD}]_{flight_ent} \boxed{1} \rangle \\ \text{COMPS} \quad \langle \rangle \end{array} \right] \\ \text{CONT} \quad act_depart \left[\begin{array}{c} \text{ARG1} \quad \boxed{1} \end{array} \right] \end{array} \right] \end{array} \right] \\ \text{QSTORE} \quad \{ \} \end{array} \right]$$

In the airport domain, there are actually two habitual signs for “to depart”, one where “to depart” requires an “at ... ” prepositional-phrase complement (as in (4.150)), and one where “to depart” requires a “from ... ” prepositional-phrase complement (this is needed in (4.152)). There are also two non-habitual signs of “to depart”, one where “to depart” requires no complement (as in (4.151)), and one where “to depart” requires a “from ... ” prepositional-phrase complement (needed in (4.153)). For simplicity, here I ignore these extra signs.

(4.152) BA737 (habitually) departs from gate 2.

(4.153) BA737 (actually) departed from gate 2.

(4.150), (4.151), and the simple-past lexical rules of section 4.7.1 give rise to two signs (a habitual and a non-habitual one) for the simple past “departed”. These are the same as (4.150) and (4.151), except that they contain additional *Past* operators. In contrast, the simple-present lexical rule of section 4.7.1 generates only one sign for the simple present “departs”. This is the same as (4.150), except that it contains an additional *Pres* operator. No simple-present sign is generated from (4.151), because the simple-present lexical rule requires the aspect of the base sign to be state.

The non-habitual simple-past sign of “departed”, the “at” sign of (4.110), and the “5:00pm” sign of (4.111), cause (4.146) to be mapped to (4.154), which expresses the non-habitual reading of (4.146). In this case, “at 5:00pm” is treated as a temporal-adverbial modifier of “BA737 departed”, as discussed in section 4.11.1.

$$(4.154) \quad Part[5:00pm, fv^v] \wedge At[fv^v, Past[e^v, act_depart(ba737)]]$$

In the habitual reading of (4.146), where the habitual sign of “departed” (derived from (4.150)) is used, “at 5:00pm” is treated as a prepositional-phrase complement of

“departed”. In this case, the sign of “at” that introduces non-predicative prepositional-phrase complements (i.e. (4.59)) is used. The intention is to map (4.146) to (4.155), where *5:00pm* is a constant acting as a “generic representative” of 5:00pm minutes (section 3.18).

$$(4.155) \quad \text{Past}[e^v, \text{hab_departs_at}(\text{ba737}, 5:00\text{pm})]$$

The problem is that in this case the “5:00pm” sign of (4.111) cannot be used, because it inserts a *Part* operator in QSTORE. The semantics principle would cause this *Part* operator to be inherited by the sign of the overall (4.146), and thus the *Part* operator would appear in the resulting formula. In contrast, (4.155) (the intended formula for (4.146)) contains no *Part* operators. To solve this problem, one has to allow an extra sign for “5:00pm”, shown in (4.156), which does not introduce a *Part*. Similarly, an extra “Monday” sign is needed in (4.148). (The fact that these extra signs have to be introduced is admittedly inelegant. This is caused by the fact that “at 5:00pm” is treated differently in (4.154) and (4.155); see also the discussion in section 3.18.) The “5:00pm” sign of (4.156), the “at” sign that is used when “at” introduces non-predicative prepositional-phrase complements (i.e. (4.59)), and the habitual “departed” sign (derived from (4.150)) cause (4.146) to be mapped to (4.155).

$$(4.156) \quad \left[\begin{array}{cc} \text{PHON} & \langle 5:00\text{pm} \rangle \\ & \left[\begin{array}{cc} \text{CAT} & \left[\begin{array}{cc} \text{HEAD} & \left[\begin{array}{cc} \text{PRD} & - \end{array} \end{array} \right] \\ & \text{noun} \end{array} \right] \\ & \text{SPR} & \langle \rangle \\ & \text{SUBJ} & \langle \rangle \\ & \text{COMPS} & \langle \rangle \end{array} \right] \\ \text{SYNSEM} | \text{LOC} & \left[\begin{array}{cc} \text{CONT} & \left[\begin{array}{cc} \text{INDEX} & 5:00\text{pm} \\ \text{RESTR} & \{ \} \end{array} \right] \\ & \text{nom_obj} \end{array} \right] \\ \text{QSTORE} & \{ \} \end{array} \right]$$

The habitual “departed” sign (which derives from (4.150)) requires the index of the prepositional-phrase complement to be of sort *minute_gappy*. As wanted, this does not allow the “5:00pm” sign of (4.111) (the one that introduces a *Part*) to be used in the prepositional-phrase complement of the habitual “departed”, because if (4.111) is used, the index of the prepositional phrase will be of sort *minute_ent_var*, which is not a subsort of *minute_gappy* (see figure 4.4 on page 126). In contrast, (4.156) introduces an index of sort *5:00pm*, which is a subsort of *minute_gappy*, and hence that sign can be used in the complement of the habitual “departed”.

The treatment of the simple present (4.147) is similar. In this case, the habitual simple present sign (that is derived from (4.150)) is used, and (4.147) is mapped to (4.157). No TOP formula is generated for the (impossible) non-habitual reading of (4.147), because there is no non-habitual sign for the simple present “*departs*” (see comments above about the simple present lexical rule).

(4.157) *Pres[hab_departs_at(ba737, 5:00pm)]*

4.13 Fronted temporal modifiers

As discussed in section 4.11, in this thesis temporal-adverbial modifiers (e.g. “*at 5:00pm*” in (4.158) – (4.159), “*on Monday*” in (4.160) – (4.161)) can modify either whole finite sentences or past participle verb phrases.

(4.158) BA737 entered sector 2 at 5:00pm.

(4.159) At 5:00pm BA737 entered sector 2.

(4.160) Tank 2 was empty on Monday.

(4.161) On Monday tank 2 was empty.

In HPSG, the order in which a modifier and the constituent to which the modifier attaches can appear in a sentence is controlled by the “constituent-ordering principle” (COP). This is a general (and not fully developed) principle that controls the order in which the various constituents can appear in a sentence (see chapter 7 of [Pollard & Sag 87]). This thesis uses an over-simplified version of COP, that places no restriction on the order between temporal modifiers and modified constituents when the modified constituents are sentences. This allows “*at 5:00pm*” to either follow “*BA737 entered sector 2*” (as in (4.158)), or to precede it (as in (4.159)). Similarly, “*on Monday*” may either follow “*tank 2 was empty*” (as in (4.160)), or precede it (as in (4.161)).⁹ When temporal modifiers attach to past-participle verb phrases, however, I require the modifiers to follow the verb phrases, as in (4.162). This rules out unacceptable sentences like (4.163), where “*at 5:00pm*” precedes the “*entered sector 2*”.¹⁰

⁹ An alternative approach is to allow temporal modifiers to participate in unbounded dependency constructions; see pp. 176 – 181 of [Pollard & Sag 94].

¹⁰ Constituent-ordering restrictions are enforced in the ALE grammar of the prototype NLITDB in a rather ad hoc manner, which involves partitioning the *synsem* sort into *pre_mod_synsem* and

(4.162) BA737 had [[entered sector 2] at 5:00pm].

(4.163) *BA737 had [at 5:00pm [entered sector 2]].

This approach causes (4.164) to receive only (4.165), because in (4.164) “at 5:00pm” can modify only the whole “BA737 had entered sector 2” (it cannot modify just “entered sector 2” because of the intervening “BA737 had”). In (4.165), 5:00pm is a reference time, a time where the entrance had already occurred. In contrast, (4.166) receives both (4.165) and (4.167), because in that case “at 5:00pm” can modify either the whole “BA737 had entered sector 2” or only “entered sector 2”. In (4.167), 5:00pm is the time where the entrance occurred.

(4.164) At 5:00pm [BA737 had entered sector 2].

(4.165) $Part[5:00pm, fv^v] \wedge At[fv^v, Past[e1^v, Perf[e2^v, enter(ba737, sector2)]]]$

(4.166) BA737 had entered sector 2 at 5:00pm.

(4.167) $Part[5:00pm, fv^v] \wedge Past[e1^v, Perf[e2^v, At[fv^v, enter(ba737, sector2)]]]$

The fact that (4.164) does not receive (4.167) does not seem to be a disadvantage, because in (4.164) the reading where “at 5:00pm” specifies the time of the entrance seems unlikely (or at least much more unlikely than in (4.166)).

4.14 Temporal subordinate clauses

I now discuss temporal subordinate clauses (section 2.10), focusing on “while ... ” clauses. The treatment of “before ... ” and “after ... ” clauses is very similar.

As with period adverbials, “while ... ” clauses are treated as temporal modifiers of finite sentences or past participle verb phrases. As with prepositions introducing period adverbials, “while” is given two signs. The first one, shown in (4.168), introduces an *End* operator, causes an aspectual shift to point, and can be used only with culminating activity main clauses ((4.168) is similar to (4.127).) The second one is the same as (4.168), except that it does not introduce an *End*, it preserves the aspectual class of the main clause, and it can be used with main clauses of any aspectual class. In both cases, “while” requires as its complement a finite sentence whose aspect must not

post_mod_synsem, and using feature structures from the two subsorts as values of MOD to signal that the modifier can only precede or follow the modified constituent. This idea was borrowed from a grammar written by Suresh Manandhar.

be consequent state (this agrees with table 2.6 on page 56, which does not allow the aspectual class of the “while”-clause to be consequent state).

$$(4.168) \left[\begin{array}{l} \text{PHON} \quad \langle \textit{while} \rangle \\ \\ \text{SYNSEM} \mid \text{LOC} \\ \\ \text{QSTORE} \quad \{ \} \end{array} \left[\begin{array}{l} \text{CAT} \\ \\ \text{CONT} \end{array} \left[\begin{array}{l} \text{HEAD} \left[\begin{array}{l} \text{MOD} \quad \text{S} \left[\begin{array}{l} \text{VFORM} \quad \textit{fin} \end{array} \right] : [2] \vee \text{VP} \left[\begin{array}{l} \text{VFORM} \quad \textit{psp} \end{array} \right] : [2] \\ \text{MOD} \mid \text{LOC} \mid \text{CAT} \mid \text{ASPECT} \quad \textit{culmact} \end{array} \right] \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \rangle \\ \text{COMPS} \quad \langle \text{S} \left[\begin{array}{l} \text{VFORM} \quad \textit{fin} \\ \text{ASPECT} \quad \neg \textit{cnsq_state} \end{array} \right] : [1] \rangle \\ \text{ASPECT} \quad \textit{point} \\ \text{TIME_SPEC} \quad [1] \\ \text{MAIN_PSOA} \quad \left[\begin{array}{l} \text{MAIN_PSOA} \quad [2] \\ \textit{at_op} \quad \textit{end} \end{array} \right] \end{array} \right] \end{array} \right]$$

The [1] in (4.168) denotes the CONT of the sign of the complement of “while” (the subordinate clause). The two “while” signs cause (4.169) to receive (4.170) and (4.171). (“To land” is a culminating activity verb in the airport domain). (4.170) requires the landing to have simply been completed during the inspection, while (4.171) requires the landing to have both started and been completed during the inspection.

(4.169) UK160 landed while J.Adams was inspecting BA737.

(4.170) $At[Past[e1^v, inspecting(j_adams, ba737)],$
 $End[Past[e2^v, Culm[landing(occr^v, uk160)]]]]$

(4.171) $At[Past[e1^v, inspecting(j_adams, ba737)],$
 $Past[e2^v, Culm[landing(occr^v, uk160)]]]$

Since “while ... ” clauses are treated as temporal modifiers, the ordering arrangements of section 4.13 apply to “while ... ” clauses as well. Hence, “while ... ” clauses can either precede or follow finite sentences (e.g. (4.172), (4.173)).

(4.172) UK160 arrived while J.Adams was inspecting BA737.

(4.173) While J.Adams was inspecting BA737, UK160 arrived.

One problem with the present treatment of “while ... ” clauses is that it maps (4.174) to (4.175), which requires the inspection to have been completed. This does not agree with table 2.6 on page 56, according to which any requirement that the situation of a

culminating activity sentence must have been reached is cancelled when the sentence is used as a “while ... ” clause. To overcome this problem, the post-processing (section 4.17 below) removes any *Culm* operators that are within first arguments of *At* operators. This removes the *Culm* of (4.175), generating a formula that no longer requires the inspection to have been completed.

(4.174) UK160 departed while J.Adams inspected BA737.

(4.175) $At[Past[e1^v, Culm[inspecting(j_adams, ba737)]],$
 $Past[e2^v, [actl_depart(uk160)]]]$

4.15 Interrogatives

So far, this chapter has considered mainly assertions (e.g. (4.176)). (The reader is reminded that assertions are treated as yes/no questions; e.g. (4.176) is treated as (4.177).) I now explain how the HPSG version of this thesis copes with questions (e.g. (4.177) – (4.182)).

(4.176) Tank 2 was empty.

(4.177) Was tank 2 empty?

(4.178) Did J.Adams inspect BA737?

(4.179) Which tank was empty?

(4.180) Who inspected BA737?

(4.181) What did J.Adams inspect?

(4.182) When did J.Adams inspect BA737?

Yes/no questions (e.g. (4.177), (4.178)) constitute no particular problem. HPSG’s schemata allow auxiliary verbs to be used in sentence-initial positions, and cause (4.177) to receive the same formula (shown in (4.184)) as (4.183). In both cases, the same lexical signs are used. Similar comments apply to (4.178) and (4.185), which are mapped to (4.186).

(4.183) Tank 2 was empty.

(4.184) $Past[e^v, empty(tank2)]$

(4.185) J.Adams did inspect BA737.

(4.186) $Past[e^v, Culm[inspecting(occr^v, j_adams, ba737)]]$

The interrogative “*which*” is treated syntactically as a determiner of (non-predicative) noun phrases. The sign of “*which*” is the same as the sign of “*the*” of (4.65), except that it introduces an interrogative quantifier rather than an existential one. For example, (4.179) is analysed syntactically in the same way as (4.187) (punctuation is ignored). However, the formula of (4.179) (shown in (4.189)) contains an additional interrogative quantifier (cf. the formula of (4.187), shown in (4.188)). (I assume here that “*tank*” does not introduce an *Ntense*. The “*a*” of (4.187) introduces an existential quantifier which is removed during the extraction of (4.188) from the sign of (4.187), as discussed in section 4.6.)

(4.187) A tank was empty.

(4.188) $tank(tk^v) \wedge Past[e^v, empty(tk^v)]$

(4.189) $?tk^v tank(tk^v) \wedge Past[e^v, empty(tk^v)]$

The interrogative “*who*” is treated syntactically as a non-predicative noun-phrase. Its sign, shown in (4.190), introduces an interrogative quantifier.

(4.190)
$$\left[\begin{array}{l} \text{PHON} \quad \langle who \rangle \\ \\ \text{SYNSEM} \mid \text{LOC} \quad \left[\begin{array}{l} \text{CAT} \quad \left[\begin{array}{l} \text{HEAD} \quad \left[\begin{array}{l} \text{PRD} \quad - \end{array} \right] \\ \text{noun} \end{array} \right] \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \rangle \\ \text{COMPS} \quad \langle \rangle \end{array} \right] \\ \text{CONT} \quad \left[\begin{array}{l} \text{INDEX} \quad \text{person_ent} \quad \left[\text{TVAR} \quad + \right] \\ \text{RESTR} \quad \{ \} \end{array} \right] \end{array} \right] \\ \\ \text{QSTORE} \quad \left\{ \begin{array}{l} \text{DET} \quad \text{interrog} \\ \text{RESTIND} \quad \boxed{\square} \end{array} \right\} \end{array} \right]$$

(4.180) is analysed syntactically in the same way as (4.191). The sign of “*who*”, however, gives rise to an interrogative quantifier in the formula of (4.180) (shown in (4.193)), which is not present in the formula of (4.191) (shown in (4.192)). The interrogative “*what*” is treated similarly.

(4.191) J.Adams inspected BA737.

(4.192) $Past[Culm[inspecting(occr^v, j_adams, ba737)]]$

(4.193) ? wh^v Past[Culm[*inspecting*($occr^v$, wh^v , *ba737*)]]

The HPSG version of this thesis admits questions like (4.194), which are unacceptable in most contexts. (4.194) is licensed by the same syntactic analysis that allows (4.195), and receives the same formula as (4.196).

(4.194) ?Did J.Adams inspect which flight?

(4.195) Did J.Adams inspect a flight?

(4.196) Which flight did J.Adams inspect?

Questions like (4.196), where the interrogative refers to the object of the verb, are treated using HPSG’s unbounded-dependencies mechanisms (more precisely, using the SLASH feature; see chapter 4 of [Pollard & Sag 94]).¹¹ Roughly speaking, (4.196) is analysed as being a form of (4.194), where the object “*which flight*” has moved to the beginning of the question. HPSG’s unbounded-dependencies mechanisms will not be discussed here (see [Pollard & Sag 94]; the prototype NLITDB uses the traceless analysis of unbounded dependencies, presented in chapter 9 of [Pollard & Sag 94]).

The present treatment of interrogatives allows questions with multiple interrogatives, like (4.197) which receives (4.198). ((4.197) is parsed in the same way as (4.199).) Unfortunately, it also allows ungrammatical questions like (4.200), which is treated as a version of (4.197) where the “*what*” complement has moved to the beginning of the sentence. ((4.200) receives (4.197).)

(4.197) Who inspected what.

(4.198) ? $w1^v$? $w2^v$ Past[e^v , Culm[*inspecting*($occr^v$, $w1^v$, $w2^v$)]]

(4.199) J.Adams inspected BA737.

(4.200) *What who inspected.

The interrogative “*when*” of (4.201) is treated as a temporal-adverbial modifier of finite sentences. (4.203) shows the sign of “*when*” that is used in (4.201). (4.203) causes (4.201) to receive (4.202).

¹¹ Pollard and Sag also reserve a QUE feature, which is supposed to be used in the treatment of interrogatives. They provide virtually no information on the role of QUE, however, pointing to [Ginzburg 92] where QUE is used in a general theory of interrogatives. Ginzburg’s theory is intended to address issues well beyond the scope of this thesis (e.g. the relation between a question and the facts that can be said to *resolve* that question; see also [Ginzburg 95a], [Ginzburg 95b]). QUE is not used in this thesis.

(4.201) When was tank 2 empty?

(4.202) $?_{mxl}w^v \text{ Past}[e^v, \text{empty}(\text{tank2})]$

(4.203)
$$\left[\begin{array}{l} \text{PHON} \quad \langle \text{when} \rangle \\ \\ \text{SYNSEM} \mid \text{LOC} \quad \left[\begin{array}{l} \text{CAT} \quad \left[\begin{array}{l} \text{HEAD} \quad \left[\begin{array}{l} \text{MOD} \quad \text{s}[\text{VFORM } fn]:\boxed{1} \\ \text{MOD} \mid \text{LOC} \mid \text{CAT} \mid \text{ASPECT} \quad \boxed{2} \end{array} \right] \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \rangle \\ \text{COMPS} \quad \langle \rangle \\ \text{ASPECT} \quad \boxed{2} \end{array} \right] \\ \text{CONT} \quad \boxed{1} \end{array} \right] \end{array} \right] \end{array} \right]$$

$$\left[\begin{array}{l} \text{QSTORE} \quad \left\{ \left[\begin{array}{l} \text{DET} \quad \text{interrog_mxl} \\ \text{RESTIND} \quad \left[\begin{array}{l} \text{INDEX} \quad \text{temp_ent} \left[\text{TVAR} \quad + \right] \\ \text{RESTR} \quad \{ \} \end{array} \right] \end{array} \right] \right\} \end{array} \right]$$

(4.203) introduces interrogative-maximal quantifiers whose variables (w^v in (4.202)) do not appear elsewhere in the formula. The post-processing (to be discussed in section 4.17) replaces the variables of interrogative-maximal quantifiers by variables that appear as first arguments of *Past* or *Perf* operators. In (4.202), this would replace w^v by e^v , generating a formula that asks for the maximal past periods where tank 2 was empty.

There is also a second sign for the interrogative “when” (shown in (4.206)), that is used in habitual questions like (4.204). In (4.204), “when” is taken to play the same role as “at 5:00pm” in (4.205), i.e. it is treated as the prepositional-phrase complement of the habitual “depart” (see section 4.12), which has moved to the beginning of the sentence via the unbounded-dependencies mechanisms.

(4.204) When does BA737 depart (habitually)?

(4.205) Does BA737 depart (habitually) at 5:00pm?

$$(4.206) \left[\begin{array}{l} \text{PHON} \quad \langle \textit{when} \rangle \\ \\ \text{SYNSEM} \mid \text{LOC} \\ \\ \text{QSTORE} \quad \left\{ \left[\begin{array}{l} \text{DET} \quad \textit{interrog} \\ \text{RESTIND} \quad \boxed{1} \end{array} \right] \right\} \end{array} \right] \left[\begin{array}{l} \\ \\ \left[\begin{array}{l} \text{CAT} \\ \\ \text{CONT} \end{array} \right] \left[\begin{array}{l} \text{HEAD} \quad \textit{prep} \quad \left[\begin{array}{l} \text{PRD} \quad - \end{array} \right] \\ \text{SPR} \quad \langle \rangle \\ \text{SUBJ} \quad \langle \rangle \\ \text{COMPS} \quad \langle \rangle \end{array} \right] \\ \\ \left[\begin{array}{l} \text{INDEX} \quad \textit{gappy-partng} \quad \left[\begin{array}{l} \text{TVAR} \quad + \end{array} \right] \\ \text{RESTR} \quad \{ \} \end{array} \right] \end{array} \right] \left[\begin{array}{l} \\ \\ \boxed{1} \end{array} \right] \end{array} \right]$$

In the simple past (4.207), both the (state) habitual homonym of “*to depart*” (that of (4.150), which requires a prepositional phrase complement) and the (point) non-habitual homonym (that of (4.151), which requires no complement) can be used. Hence, “*when*” can be either a prepositional-phrase complement of the habitual “*depart*” (using (4.206)), or a temporal modifier of the non-habitual sentence “*did BA737 depart*” (using (4.203)). This gives rise to (4.208) and (4.209), which correspond to the habitual and non-habitual readings of (4.207) (the w^v of (4.209) would be replaced by e^v during the post-processing).

(4.207) When did BA737 depart?

(4.208) $?w^v \textit{Past}[e^v, \textit{hab_departs_at}(\textit{ba737}, w^v)]$

(4.209) $?_{\textit{maxl}} w^v \textit{Past}[e^v, \textit{actl_depart}(\textit{ba737})]$

4.16 Multiple temporal modifiers

The framework of this thesis currently runs into several problems in sentences with multiple temporal modifiers. This section discusses these problems.

Both preceding and trailing temporal modifiers: Temporal modifiers are allowed to either precede or follow finite sentences (section 4.13). When a finite sentence is modified by both a preceding and a trailing temporal modifier (as in (4.210)), two parses are generated: one where the trailing modifier attaches first to the sentence (as in (4.211)), and one where the preceding modifier attaches first (as in (4.213)). In most cases, this generates two semantically equivalent formulae ((4.212) and (4.214) in the case of (4.210)). A mechanism is needed to eliminate one of the two formulae.

- (4.210) Yesterday BA737 was at gate 2 for two hours.
- (4.211) Yesterday [[BA737 was at gate 2] for two hours.]
- (4.212) $At[yesterday, For[hour^c, 2, Past[e^v, located_at(ba737, gate2)]]]$
- (4.213) [Yesterday [BA737 was at gate 2]] for two hours.
- (4.214) $For[hour^c, 2, At[yesterday, Past[e^v, located_at(ba737, gate2)]]]$

Multiple temporal modifiers and anaphora: Another problem is that a question like (4.215) is mapped to (4.216). (I assume here that “flight” does not introduce an *Ntense*.) The problem with (4.216) is that it does not require fv^v to be the particular 5:00pm-minute of 2/11/95. (4.216) requires the flight to have arrived on 2/11/95 and after an arbitrary 5:00pm-minute (e.g. the 5:00pm-minute of 1/11/95). In effect, this causes the “after 5:00pm” to be ignored.

- (4.215) Which flight arrived after 5:00pm on 2/11/95?
- (4.216) $?fl^v flight(fl^v) \wedge Part[5:00pm^g, fv^v] \wedge$
 $At[2/11/95, After[fv^v, Past[e^v, arrive(fl^v)]]]$

This problem seems related to the need for temporal anaphora resolution mechanisms (section 2.12). In (4.217), for example, the user most probably has a particular (contextually-salient) 5:00pm-minute in mind, and an anaphora resolution mechanism is needed to determine that minute. A similar mechanism could be responsible for reasoning that in (4.215) the most obvious contextually salient 5:00pm-minute is that of 2/11/95.

- (4.217) Which tanks were empty before/at/after 5:00pm?

Culminating activity with both punctual and period adverbial: A further problem appears when a culminating activity is modified by both a punctual and a period adverbial.¹² The problem is that, unlike what one would expect, (4.218) and (4.219) do not receive equivalent TOP formulae. (I assume here that “to repair” is classified as culminating activity verb.)

- (4.218) J.Adams repaired fault 2 at 5:00pm on 2/11/95.

¹² The problems of this section that involve period adverbials also arise when temporal subordinate clauses are used instead of period adverbials.

(4.219) J.Adams repaired fault 2 on 2/11/95 at 5:00pm.

In (4.218), the punctual adverbial “at 5:00pm” modifies the culminating activity sentence “J.Adams repaired fault 2”. The punctual adverbial causes “J.Adams repaired fault 2 at 5:00pm” to become a point (see table 2.2 on page 44). Two formulae are generated: one that requires the repair to have started at 5:00pm, and one that requires the repair to have been completed at 5:00pm. “On 2/11/95” then modifies the point expression “J.Adams repaired fault 2 at 5:00pm”. This leads to (4.220) and (4.221). In (4.220) the repair *starts* at the 5:00pm-minute of 2/11/95, while in (4.221) the repair is *completed* at the 5:00pm-minute of 2/11/95. (The first reading is easier to accept in “J.Adams inspected BA737 at 5:00pm on 2/11/95”.)

(4.220) $Part[5:00pm^g, fv^v] \wedge At[2/11/95,$
 $At[fv^v, Begin[Past[e^v, Culm[repairing(occr^v, j_adams, fault2)]]]]]$

(4.221) $Part[5:00pm^g, fv^v] \wedge At[2/11/95,$
 $At[fv^v, End[Past[e^v, Culm[repairing(occr^v, j_adams, fault2)]]]]]$

(A digression: this example also demonstrates why punctual adverbials are taken to trigger an aspectual shift to point; see section 2.9.1. Without this shift, the aspectual class of “J.Adams repaired fault 2 at 5:00pm” would be culminating activity, and the “on” signs of section 4.11.2 would lead to the additional formulae of (4.222) and (4.223). These are equivalent to (4.220) and (4.221) respectively.)

(4.222) $Part[5:00pm^g, fv^v] \wedge At[2/11/95,$
 $End[At[fv^v, Begin[Past[e^v, Culm[repairing(occr^v, j_adams, fault2)]]]]]$

(4.223) $Part[5:00pm^g, fv^v] \wedge At[2/11/95,$
 $End[At[fv^v, End[Past[e^v, Culm[repairing(occr^v, j_adams, fault2)]]]]]$

In (4.219), “J.Adams repaired fault 2” is first modified by the period adverbial “on 2/11/95”. Two formulae (shown in (4.224) and (4.225)) are generated. (4.224) requires the repair to simply reach its completion on 2/11/95, while (4.225) requires the repair to both start and reach its completion on 2/11/95. In the first case (where (4.224) is generated), the aspectual class of “J.Adams repaired fault 2 on 2/11/95” becomes point, while in the other case the aspectual class remains culminating activity (see also table 2.3 on page 49).

(4.224) $At[2/11/95, End[Past[e^v, Culm[repairing(occr^v, j_adams, fault2)]]]]]$

$$(4.225) \quad At[2/11/95, Past[e^v, Culm[repairing(occr^v, j_adams, fault2)]]]$$

In the case of (4.224), where the aspectual class of “*J.Adams repaired fault 2 on 2/11/95*” is point, the signs of section 4.11.1 lead to (4.226), while in the case of (4.225), they lead to (4.227) and (4.228).

$$(4.226) \quad Part[5:00pm^g, fv^v] \wedge At[fv^v, \\ At[2/11/95, End[Past[e^v, Culm[repairing(occr^v, j_adams, fault2)]]]]]$$

$$(4.227) \quad Part[5:00pm^g] \wedge At[fv^v, \\ Begin[At[2/11/95, Past[e^v, Culm[repairing(occr^v, j_adams, fault2)]]]]]$$

$$(4.228) \quad Part[5:00pm^g] \wedge At[fv^v, \\ End[At[2/11/95, Past[e^v, Culm[repairing(occr^v, j_adams, fault2)]]]]]$$

Hence, (4.218) receives two formulae ((4.220) and (4.221)), while (4.219) receives three ((4.226) – (4.228)). (4.226) is equivalent to (4.221). They both require the repair to reach its completion within the 5:00pm-minute of 2/11/95. Unlike what one might expect, however, (4.227) is not equivalent to (4.220). (4.227) requires a past period that covers exactly the whole repair (from start to completion) to fall within 2/11/95, and the beginning of that period to fall within some 5:00pm-minute. This means that the repair must start at the 5:00pm-minute of 2/11/95 (as in (4.220)), but it also means that the repair must reach its completion within 2/11/95 (this is not a requirement in (4.220)). Also, unlike what one might expect, (4.228) is not equivalent to (4.221) and (4.226). (4.228) requires the repair to reach its completion within the 5:00pm-minute of 2/11/95 (as in (4.221) and (4.226)), but it also requires the repair to start within 2/11/95 (which is not a requirement in (4.221) and (4.226)).

The differences in the number and semantics of the generated formulae in (4.218) and (4.219) lead to differences in the behaviour of the NLITDB that are difficult to explain to the user. A tentative solution is to adopt some mechanism that would reorder the temporal modifiers, so that the punctual adverbial attaches before the period one. This would reverse the order of “*on 2/11/95*” and “*at 5:00pm*” in (4.219), and would cause (4.219) to be treated in the same way as (4.218) (i.e. to be mapped to (4.220) and (4.221)); these seem to capture the most natural readings of (4.218) and (4.219)).

Culminating activity and multiple period adverbials: A further problem is that a sentence like (4.229), where a culminating activity is modified by two period

adverbials, receives three formulae, shown in (4.230) – (4.232). It turns out that (4.231) is equivalent to (4.232), and hence one of the two should be eliminated.

(4.229) J.Adams repaired fault 2 in June in 1992.

(4.230) $Part[june^g, j^v] \wedge At[1992,$
 $At[j^v, End[Past[e^v, Culm[repairing(occr^v, j_adams, fault2)]]]]]$

(4.231) $Part[june^g, j^v] \wedge At[1992,$
 $End[At[j^v, Past[e^v, Culm[repairing(occr^v, j_adams, fault2)]]]]]$

(4.232) $Part[june^g, j^v] \wedge At[1992,$
 $At[j^v, Past[e^v, Culm[repairing(occr^v, j_adams, fault2)]]]]]$

A period adverbial combining with a culminating activity can either insert an *End* operator and cause an aspectual shift to point, or insert no *End* and leave the aspectual class unchanged (see section 4.11.2). In the case where (4.230) is generated, “in June” inserts an *End* and changes the aspectual class to point. This does not allow “in 1992” (which attaches after “in June”) to insert an *End*, because period adverbials combining with points are not allowed to insert *Ends* (the “on” sign of (4.127) cannot be used with points). In the cases where (4.231) or (4.232) are generated, “in June” does not insert an *End*, and the aspectual class remains culminating activity. “In 1992” can then insert an *End* (as in (4.231)) or not (as in (4.232)). (4.232) requires the whole repair to be located within a June and 1992 (i.e. within the June of 1992). (4.230) is weaker: it requires only the completion point of the repair to be located within the June of 1992. Finally, (4.231) requires the whole of the repair to be located within a June, and the completion point of the repair to fall within 1992. This is equivalent to requiring the whole of the repair to fall within the June of 1992, i.e. (4.231) is equivalent to (4.232), and one of the two should be eliminated.

4.17 Post-processing

The parsing maps each English question to an HPSG sign (or multiple signs, if the parser understands the question to be ambiguous). From that sign, a TOP formula is extracted as discussed in section 4.6. The extracted formula then undergoes an additional post-processing phase. This is a collection of minor transformations, discussed below, that cannot be carried out easily during the parsing.

Removing Culms: (4.234) shows the TOP formula that is extracted from the sign of (4.233). As discussed in section 4.11.3, (4.234) does not represent correctly (4.233), because (4.234) requires the taxiing to have been completed. In contrast, as discussed in section 2.9.3, the “for ... ” adverbial of (4.233) cancels the normal implication of “BA737 taxied to gate 2” that the taxiing must have been completed. To express correctly (4.233), the *Culm* of (4.234) has to be removed.

(4.233) BA737 taxied to gate 2 for five minutes.

(4.234) $For[minute^c, 5, Past[e^v, Culm[taxiing_to(ba737, gate2)]]]$

A first solution would be to remove during the post-processing any *Culm* operator that is within the scope of a *For* operator. The problem with this approach is that duration “in ... ” adverbials also introduce *For* operators (see section 4.11.3), but unlike “for ... ” adverbials they do not cancel the implication that the completion must have been reached. For example, the formula extracted from the sign of (4.235) is (4.234). In this case, (4.234) is a correct rendering of (4.235) (because (4.235) *does* imply that BA737 reached gate 2), and hence the *Culm* operator should not be removed. To overcome this problem, the prototype NLITDB attaches to each *For* operator a flag showing whether it was introduced by a “for ... ” or an “in ... ” adverbial. Only *For* operators introduced by “for ... ” adverbials cause *Culm* operators within their scope to be removed.

(4.235) BA737 taxied to gate 2 in five minutes.

The post-processing also removes any *Culm* operator from within the first argument of an *At* operator. As explained in section 4.14, this is needed to express correctly “while ... ” clauses.

?_{mxl} quantifiers: As noted in section 4.15, before the post-processing the variables of interrogative-maximal quantifiers introduced by “when” do not occur elsewhere in their formulae. For example, (4.237) and (4.238) are extracted from the signs of (4.236) and (4.238). In both formulae, w^v occurs only immediately after the ?_{mxl}.

(4.236) When was J.Adams a manager?

(4.237) $?_{mxl}w^v Past[e^v, manager(j_adams)]$

(4.238) When while BA737 was circling was runway 2 open?

$$(4.239) \quad ?_{mxl}w^v \text{ At}[\text{Past}[e1^v, \text{circling}(\text{ba737})], \text{Past}[e2^v, \text{open}(\text{runway2})]]$$

During the post-processing, the variables of interrogative-maximal quantifiers are replaced by variables that appear as first arguments of *Past* or *Perf* operators, excluding *Past* and *Perf* operators that are within first arguments of *At*, *Before*, or *After* operators. In (4.237), this causes w^v to be replaced by e^v . The resulting formula asks for the maximal past periods where J.Adams was a manager. Similarly, the w^v of (4.239) is replaced by $e2^v$. The resulting formula asks for the maximal past periods $e2^v$, such that runway 2 was open at $e2^v$, and $e2^v$ is a subperiod of a period $e1^v$ where BA737 was circling. In (4.239), w^v cannot be replaced by $e1^v$, because $\text{Past}[e1^v, \text{circling}(\text{ba737})]$ is within the first argument of an *At*.

Past and *Perf* operators located within first arguments of *At*, *Before*, or *After* operators are excluded, to avoid interpreting “when” as referring to the time where the situation of a subordinate clause held (formulae that express subordinate clauses end-up within first arguments of *At*, *Before*, or *After* operators). The interrogative “when” always refers to the situation of the main clause. For example, (4.238) cannot be asking for maximal periods where BA737 was circling that subsume periods where runway 2 was open (this would be the meaning of (4.239) if w^v were replaced by $e1^v$).

When the main clause is in the past perfect, this arrangement allows the variable of $?_{mxl}$ to be replaced by either the first argument of the main-clause’s *Past* operator, or the first argument of the main-clause’s *Perf* operator. (4.241), for example, shows the formula extracted from the sign of (4.240). The post-processing generates two formulae: one where w^v is replaced by $e1^v$, and one where w^v is replaced by $e2^v$. The first one asks for what section 2.9.1 called the “consequent period” of the inspection (the period from the end of the inspection to the end of time). The second one asks for the time of the actual inspection.

$$(4.240) \quad \text{When had J.Adams inspected BA737?}$$

$$(4.241) \quad ?_{mxl}w^v \text{ Past}[e1^v, \text{Perf}[e2^v, \text{Culm}[\text{inspecting}(\text{occr}^v, j_adams, \text{ba737})]]]$$

Ntense operators: As noted in section 4.9.1, when extracting TOP formulae from signs, if an *Ntense* operator is encountered and the sign contains no definite indication that the first argument of the *Ntense* should be *now**, in the extracted formula the first argument of the *Ntense* becomes a variable. That variable does not occur elsewhere

in the extracted formula. Assuming, for example, that the (non-predicative) “queen” introduces an *Ntense*, the formula extracted from the sign of (4.242) is (4.243). The t^v of the *Ntense* does not occur elsewhere in (4.243).

(4.242) The queen was in Rome.

(4.243) $Ntense[t^v, queen(q^v)] \wedge Past[e1^v, located_at(q^v, rome)]$

During the post-processing, variables appearing as first arguments of *Ntenses* give rise to multiple formulae, where the first arguments of the *Ntenses* are replaced by *now** or by first arguments of *Past* or *Perf* operators. In (4.243), for example, the post-processing generates two formulae: one where t^v is replaced by *now** (queen at the speech time), and one where t^v is replaced by e^v (queen when in Rome).

In (4.245) (the formula extracted from the sign of (4.244)), there is no *Past* or *Perf* operator, and hence t^v can only become *now**. This captures the fact that the “queen” in (4.244) most probably refers to the queen of the speech time.

(4.244) The queen is in Rome.

(4.245) $Ntense[t^v, queen(q^v)] \wedge Pres[located_at(q^v, gate2)]$

In (4.247) (the formula extracted from the sign of (4.246)), the post-processing leads to three formulae, where t^v is replaced by *now** (queen at speech time), $e2^v$ (queen during the visit), or $e1^v$ (queen at a “reference time” after the visit).

(4.246) The queen had visited Rome.

(4.247) $Ntense[t^v, queen(q^v)] \wedge Past[e1^v, Perf[e2^v, visiting(q^v, rome)]]$

4.18 Summary

This chapter has shown how HPSG can be used to translate English questions directed to a NLITDB to appropriate TOP formulae. During the parsing, each question receives one or more HPSG signs, from which TOP formulae are extracted. The extracted formulae then undergo an additional post-processing phase, which leads to formulae that capture the semantics of the original English questions.

Several modifications were made to HPSG. The main modifications were: (i) HPSG features and sorts that are intended to account for phenomena not examined in this

thesis (e.g. pronouns, relative clauses, number agreement) were dropped. (ii) The quantifier storage mechanism of HPSG was replaced by a more primitive one, that does not allow quantifiers to be unstored during the parsing; the semantics principle was modified accordingly. (iii) An ASPECT feature was added, along with a principle that controls its propagation. (iv) The possible values of CONT and QSTORE were modified, to represent TOP expressions rather than situation-theory constructs. (v) A hierarchy of world-entity types was mounted under the *ind* sort; this is used to disambiguate sentences, and to block semantically ill-formed ones. (vi) New lexical signs and lexical rules were introduced to cope with temporal linguistic mechanisms (verb tenses, temporal adverbials, temporal subordinate clauses, etc.). Apart from these modifications, the HPSG version of this thesis follows closely [Pollard & Sag 94].

Chapter 5

From TOP to TSQL2

“Time is money.”

5.1 Introduction

This chapter describes the translation from TOP to TSQL2. The discussion starts with an introduction to TSQL2 and the version of the relational model on which TSQL2 is based. This thesis adopts some modifications to TSQL2. These are described next, along with some minor alterations in the TOP definition of chapter 3. The translation from TOP to TSQL2 requires TOP’s model to be linked to the database; this is explained next. The translation is carried out by a set of rules. I explore formally the properties that these rules must possess for the translation to be correct, and I describe the intuitions behind the design of the rules. An illustration of how some of the rules work is also given. The full set of the translation rules, along with a proof that they possess the necessary properties, is given in appendix A. The chapter ends with a discussion of related work and reflections on how the generated TSQL2 code could be optimised.

5.2 An introduction to TSQL2

This section introduces TSQL2 and the version of the relational model on which TSQL2 is based. Some definitions that are not part of the TSQL2 documentation are also given; these will be used in following sections. I note that although [Snodgrass 95] defines TSQL2’s syntax rigorously, the semantics of the language is defined very informally, with parts of the semantics left to the intuition of the reader. There are

also some inconsistencies in the TSQL2 definition (several of these were pointed out in [Androutsopoulos *et al.* 95a]).

5.2.1 The traditional relational model

As explained in section 1.2.4, the traditional relational model stores information in relations, which can be thought of as tables. For example, *salaries* below is a relation showing the current salaries of a company's employees. *salaries* has two *attributes* (intuitively, columns), *employee* and *salary*. The *tuples of the relation* are intuitively the rows of the table (*salaries* has three tuples).

<i>salaries</i>	
<i>employee</i>	<i>salary</i>
<i>J.Adams</i>	17000
<i>T.Smith</i>	19000
<i>G.Papas</i>	14500

I adopt a set-theoretic definition of relations (see section 2.3 of [Ullman 88] for alternative approaches). A set of attributes \mathcal{D}_A is assumed (e.g. *employee* and *salary* are elements of \mathcal{D}_A). A *relation schema* is an ordered tuple of one or more attributes (e.g. $\langle \textit{employee}, \textit{salary} \rangle$). A set of *domains* $\mathcal{D}_D = \{D_1, D_2, \dots, D_{n_D}\}$ is also assumed. Each element D_i of \mathcal{D}_D is itself a set. For example, D_1 may contain all strings, D_2 all positive integers, etc. Each attribute (element of \mathcal{D}_A) is assigned a domain (element of \mathcal{D}_D). $D(A)$ denotes the domain of attribute A . D on its own refers to the *universal domain*, the union of all $D_i \in \mathcal{D}_D$.

A *relation* over a relation schema $R = \langle A_1, A_2, \dots, A_n \rangle$ is a subset of $D(A_1) \times D(A_2) \times \dots \times D(A_n)$, where \times denotes the cartesian product, and $D(A_1), D(A_2), \dots, D(A_n)$ are the domains of the attributes A_1, A_2, \dots, A_n respectively. That is, a relation over R is a set of tuples of the form $\langle v_1, v_2, \dots, v_n \rangle$, where $v_1 \in D(A_1), v_2 \in D(A_2), \dots, v_n \in D(A_n)$. In each tuple $\langle v_1, v_2, \dots, v_n \rangle$, v_1 is the *attribute value* of A_1 , v_2 is the attribute value of A_2 , etc. The universal domain D is the set of all possible attribute values. Assuming, for example, that *employee, salary* $\in \mathcal{D}_A$, that D_1 and D_2 are as in the previous paragraph, and that *employee* and *salary* are assigned D_1 and D_2 , r below is a relation over $\langle \textit{employee}, \textit{salary} \rangle$. (r is a mathematical representation of *salaries* above.) On its own, “relation” will be used to refer to a relation over any relation schema.

$$r = \{ \langle J.Adams, 17000 \rangle, \langle T.Smith, 19000 \rangle, \langle G.Papas, 14500 \rangle \}$$

The *arity* of a relation over R is the number of attributes in R (e.g. the arity of r is 2). The *cardinality* of a relation is the number of tuples it contains (the cardinality of r is 3). A relational *database* is a set of relations (more elaborate definitions are possible, but this is sufficient for our purposes).

I assume that every element of D (universal domain) denotes an object in the modelled world. (“Object in the world” is used here with a very loose meaning, that covers qualifications of employees, salaries, etc.) $OBJS^{db}$ is the set of all the world objects that are each denoted by a single element of D . (Some world objects may be represented in the database as collections of elements of D , e.g. as whole tuples. $OBJS^{db}$ contains only world objects that are denoted by *single* elements of D .) I also assume that a function $f_D : D \mapsto OBJS^{db}$ is available, that maps each element v of D to the world object denoted by v . f_D reflects the semantics assigned to the attribute values by the people who use the database. In practice, an element of D may denote different world objects when used as the value of different attributes. For example, 15700 may denote a salary when used as the value of *salary*, and a part of an engine when used as the value of an attribute *part_no*. Hence, the value of f_D should also depend on the attribute where the element of D is used, i.e. it should be a function $f_D : D \times \mathcal{D}_A \mapsto OBJS^{db}$. For simplicity, I overlook this detail.

I also assume that f_D is 1-1 (injective), i.e. that every element of D denotes a different world object. In practice, f_D may not be 1-1: the database may use two different attribute values (e.g. *dpt3* and *sales_dpt*) to refer to the same world object. The TOP to TSQL2 translation could be formulated without assuming that f_D is 1-1. This assumption, however, bypasses uninteresting details. By the definition of $OBJS^{db}$, any element of $OBJS^{db}$ is a world object denoted by some element of D . That is, for every $o \in OBJS^{db}$, there is a $v \in D$, such that $f_D(v) = o$, i.e. f_D is also surjective. Since f_D is both 1-1 and surjective, the inverse mapping f_D^{-1} is a function, and f_D^{-1} is also 1-1 and surjective.

5.2.2 TSQL2’s model of time

Like TOP, TSQL2 assumes that time is discrete, linear, and bounded. In effect, TSQL2 models time as consisting of *chronons*. Chronons are the shortest representable units of

time, and correspond to TOP's time-points.¹ Depending on the TSQL2 implementation, a chronon may represent a nanosecond, a day, or a whole century. Let us call the (implementation-specific) set of chronons *CHRONS*. Although not stated explicitly, it is clear from the discussion in chapter 6 of [Snodgrass 95] that $CHRONS \neq \emptyset$, that chronons are ordered by a binary precedence relation (let us call it \prec^{db}), and that $\langle CHRONS, \prec^{db} \rangle$ has the properties of transitivity, irreflexivity, linearity, left and right boundedness, and discreteness (section 3.3).

I define periods over $\langle CHRONS, \prec^{db} \rangle$ in the same way as periods over $\langle PTS, \prec \rangle$ (section 3.3). A period over $\langle CHRONS, \prec^{db} \rangle$ is a non-empty and convex set of chronons. An instantaneous period over $\langle CHRONS, \prec^{db} \rangle$ is a set that contains a single chronon. $PERIODS_{\langle CHRONS, \prec^{db} \rangle}$ and $INSTANTS_{\langle CHRONS, \prec^{db} \rangle}$ are the sets of all periods and all instantaneous periods over $\langle CHRONS, \prec^{db} \rangle$ respectively. In section 5.8, I set the point structure $\langle PTS, \prec \rangle$ of TOP's model to $\langle CHRONS, \prec^{db} \rangle$. Hence, $PERIODS_{\langle PTS, \prec \rangle}$ and $INSTANTS_{\langle PTS, \prec \rangle}$ become $PERIODS_{\langle CHRONS, \prec^{db} \rangle}$ and $INSTANTS_{\langle CHRONS, \prec^{db} \rangle}$. As in chapter 3, I write *PERIODS* and *INSTANTS* to refer to these sets, and *PERIODS** to refer to $PERIODS \cup \{\emptyset\}$.

A *temporal element* over $\langle CHRONS, \prec^{db} \rangle$ is a non-empty (but not necessarily convex) set of chronons. $TELEMS_{\langle CHRONS, \prec^{db} \rangle}$ (or simply *TELEMS*) is the set of all temporal elements over $\langle CHRONS, \prec^{db} \rangle$. Obviously, $PERIODS \subseteq TELEMS$. For every $l \in TELEMS$, $mxlpers(l)$ is the set of the *maximal periods* of l , defined as follows:

$$mxlpers(l) \stackrel{def}{=} \{p \subseteq l \mid p \in PERIODS \text{ and for no } p' \in PERIODS \text{ is it true that } p' \subseteq l \text{ and } p \sqsubset p'\}$$

The *mxlpers* symbol is overloaded. When $l \in TELEMS$, $mxlpers(l)$ is defined as above. When S is a set of periods, $mxlpers(S)$ is defined as in section 3.3.

TSQL2 supports multiple *granularities*. These correspond to TOP complete partitionings. A granularity can be thought of as a set of periods over $\langle CHRONS, \prec^{db} \rangle$ (called *granules*), such that no two periods overlap, and the union of all the periods is *CHRONS*. A lattice is used to capture relations between granularities (e.g. a year-granule contains twelve month-granules, etc; see chapter 19 of [Snodgrass 95]).

INSTANTS, also called the *granularity of chronons*, is the finest available granularity.

¹ TSQL2 distinguishes between *valid-time chronons*, *transaction-time chronons*, and *bitemporal chronons* (pairs each comprising a valid-time and a transaction-time chronon; see chapter 10 of [Snodgrass 95]). As noted in section 1.2.4, transaction-time is ignored in this thesis. Hence, transaction-time and bitemporal chronons are not used, and "chronon" refers to valid-time chronons.

TSQL2 allows periods and temporal elements to be specified at any granularity. For example, one may specify that the first day of a period is 25/11/95, and the last day is 28/11/95. If the granularity of chronons is finer than the granularity of days, the exact chronons within 25/11/95 and 28/11/95 where the period starts and ends are unknown. Similarly, if a temporal element is specified at a granularity coarser than *INSTANTS*, the exact chronon-boundaries of its maximal periods are unknown.² These are examples of *indeterminate temporal information* (see chapter 18 of [Snodgrass 95]). Information of this kind is ignored in this thesis. I assume that all periods and temporal elements are specified at the granularity of chronons, and that we know exactly which chronons are or are not included in periods and temporal elements. Granularities other than *INSTANTS* will be used only to express durations (see below).

Finally, TSQL2 uses the term *interval* to refer to a duration (see comments in section 3.1). An interval is a number of consecutive granules of some particular granularity (e.g. two day-granules, five minute-granules).

5.2.3 BCDM

As noted in section 1.2.4, numerous temporal versions of the relational model have been proposed. TSQL2 is based on a version called BCDM. Apart from the relations of the traditional relational model (section 5.2.1), which are called *snapshot relations* in TSQL2, BCDM provides *valid-time relations*, *transaction-time relations*, and *bitemporal relations*. Transaction-time and bitemporal relations are not used in this thesis (see chapter 10 of [Snodgrass 95]). Valid-time relations are similar to snapshot relations, except that they have a special extra attribute (the *implicit attribute*) that shows when the information of each tuple was/is/will be true.

A special domain $D_T \in \mathcal{D}_D$ is assumed, whose elements denote the elements of *TELEMS* (temporal elements). For every $v_t \in D_T$, $f_D(v_t) \in \text{TELEMS}$; and for every $l \in \text{TELEMS}$, $f_D^{-1}(l) \in D_T$. D_T is the domain of the implicit attribute. Since $D_T \in \mathcal{D}_D$, $D_T \subseteq D$ (D is the union of all the domains in \mathcal{D}_D). The assumptions of section 5.2.1 about f_D still hold: I assume that f_D is an injective and surjective function from D (which now includes D_T) to OBJS^{db} . Since the elements of D_T denote all the elements of *TELEMS*, $D_T \subseteq D$, and OBJS^{db} contains all the objects denoted

² To bypass this problem, in [Androutsopoulos *et al.* 95a] periods and temporal elements are defined as sets of granules (of any granularity) rather than sets of chronons.

by elements of D , it must be the case that $TELEMS \subseteq OBJS^{db}$. Then, the fact that $PERIODS \subseteq TELEMS$ (section 5.2.2) implies that $PERIODS \subseteq OBJS^{db}$.

A *valid-time relation* r over a relation-schema $R = \langle A_1, A_2, \dots, A_n \rangle$ is a subset of $D(A_1) \times D(A_2) \times \dots \times D(A_n) \times D_T$, where $D(A_1), D(A_2), \dots, D(A_n)$ are the domains of A_1, A_2, \dots, A_n . A_1, A_2, \dots, A_n are the *explicit attributes* of r . I use the notation $\langle v_1, v_2, \dots, v_n; v_t \rangle$ to refer to tuples of valid-time relations. If r is as above and $\langle v_1, v_2, \dots, v_n; v_t \rangle \in r$, then $v_1 \in D(A_1), v_2 \in D(A_2), \dots, v_n \in D(A_n)$, and $v_t \in D_T$. v_1, v_2, \dots, v_n are the *values of the explicit attributes*, while v_t is the *value of the implicit attribute* and the *time-stamp* of the tuple. In snapshot relations, all attributes count as explicit. In the rest of this thesis, “valid-time relation” on its own refers to a valid-time relation over any relation-schema.

TSQL2 actually distinguishes between *state valid-time relations* and *event valid-time relations* (see chapter 16 of [Snodgrass 95]). These are intended to model situations that have duration or are instantaneous respectively. This distinction seems particularly interesting, because it appears to capture some facets of the aspectual taxonomy of chapter 2. Unfortunately, it is also one of the most unclear and problematically defined features of TSQL2. The time-stamps of state and event valid-time relations are supposed to denote “temporal elements” and “instant sets” respectively. “Temporal elements” are said to be unions of periods, while “instant sets” simply sets of chronons (see p.314 of [Snodgrass 95]). This distinction between “temporal elements” and “instant sets” is problematic. A union of periods is a union of convex sets of chronons, i.e. simply a set of chronons. (The union of two convex sets of chronons is not necessarily convex.) Hence, one cannot distinguish between unions of periods and sets of chronons (see also section 2 of [Androutsopoulos *et al.* 95a]). In section 3.3 of [Androutsopoulos *et al.* 95a] we also argue that TSQL2 does not allow specifying whether a computed valid-time relation should be state or event. Given these problems, I chose to drop the distinction between state and event valid-time relations. I assume that the time-stamps of all valid-time relations denote temporal elements, with temporal elements being sets of chronons.

For example, assuming that the domains of *employee* and *salary* are as in section 5.2.1, *val_salaries* below is a valid-time relation over $\langle employee, salary \rangle$, shown in its tabular form (the double vertical line separates the explicit attributes from the implicit one). According to chapter 10 of [Snodgrass 95], the elements of D_T are non-atomic.

Each element v_t of D_T is in turn a set, whose elements denote the chronons that belong to the temporal element represented by v_t .

<i>val_salaries</i>		
<i>employee</i>	<i>salary</i>	
<i>J.Adams</i>	17000	$\{c_1^1, c_2^1, c_3^1, \dots, c_{n_1}^1\}$
<i>J.Adams</i>	18000	$\{c_1^2, c_2^2, c_3^2, \dots, c_{n_2}^2\}$
<i>J.Adams</i>	18500	$\{c_1^3, c_2^3, c_3^3, \dots, c_{n_3}^3\}$
<i>T.Smith</i>	19000	$\{c_1^4, c_2^4, c_3^4, \dots, c_{n_4}^4\}$
<i>T.Smith</i>	21000	$\{c_1^5, c_2^5, c_3^5, \dots, c_{n_5}^5\}$

For example, $c_1^1, c_2^1, c_3^1, \dots, c_{n_1}^1$ in the first tuple for J.Adams above represent all the chronons where the salary of J.Adams was/is/will be 17000. $\{c_1^1, c_2^1, c_3^1, \dots, c_{n_1}^1\}$ is an element of D_T . For simplicity, when depicting valid-time relations I often show (in an informal manner) the temporal elements denoted by the time-stamps rather the time-stamps themselves. *val_salaries* would be shown as below, meaning that the time-stamp of the first tuple represents a temporal element of two maximal periods, 1/1/92 to 12/6/92 and 8/5/94 to 30/10/94. (I assume here that chronons correspond to days. *now* refers to the current chronon.)

(5.1)

<i>val_salaries</i>		
<i>employee</i>	<i>salary</i>	
<i>J.Adams</i>	17000	$[1/1/92, 12/6/92] \cup [8/5/94, 30/10/94]$
<i>J.Adams</i>	18000	$[13/6/92, 7/5/94] \cup [31/10/94, \text{now}]$
<i>T.Smith</i>	21000	$[15/6/92, \text{now}]$

Two tuples $\langle v_1^1, \dots, v_n^1; v_t^1 \rangle$ and $\langle v_1^2, \dots, v_n^2; v_t^2 \rangle$ are *value-equivalent* iff if $v_1^1 = v_1^2, \dots, v_n^1 = v_n^2$. A valid-time relation is *coalesced* iff it contains no value-equivalent tuples. BCDM requires all valid-time relations to be coalesced (see p.188 of [Snodgrass 95]). For example, (5.2) is not allowed (its first and third tuples are value-equivalent). In this thesis, this BCDM restriction is dropped, and (5.2) is allowed.

(5.2)

<i>employee</i>	<i>salary</i>	
<i>J.Adams</i>	17000	$[1/1/92, 12/6/92]$
<i>J.Adams</i>	18000	$[13/6/92, 7/5/94]$
<i>J.Adams</i>	17000	$[8/5/94, 30/10/94]$
<i>J.Adams</i>	18000	$[31/10/94, \text{now}]$
<i>T.Smith</i>	21000	$[15/6/92, \text{now}]$

By the definition of D_T , the elements of D_T denote all the elements of *TELEMS* (temporal elements). Since *PERIODS* \subseteq *TELEMS*, some of the elements of D_T denote periods. D_P is the subset of all elements of D_T that denote periods.³ I also assume that

³ [Snodgrass 95] seems to adopt a different approach, where $D_P \cap D_T = \emptyset$.

there is a special value $v_\varepsilon \in D$, that is used to denote the empty set (of chronons). For example, a TSQL2 expression that computes the intersection of two non-overlapping periods evaluates to v_ε .⁴ I use D_P^* to refer to $D_P \cup \{v_\varepsilon\}$.

The following notation will prove useful:

- $VREL_P$ is the set of all valid-time relations whose time-stamps are all elements of D_P (all the time-stamps denote periods).
- $NVREL_P$ is the set of all the (intuitively, “normalised”) relations $r \in VREL_P$ with the following property: if $\langle v_1, \dots, v_n; v_t^1 \rangle \in r$, $\langle v_1, \dots, v_n; v_t^2 \rangle \in r$, and $f_D(v_t^1) \cup f_D(v_t^2) \in PERIODS$, then $v_t^1 = v_t^2$. This definition ensures that in any $r \in NVREL_P$, there is no pair of different value-equivalent tuples whose time-stamps v_t^1 and v_t^2 denote overlapping or adjacent periods (because if the periods of v_t^1 and v_t^2 overlap or they are adjacent, their union is also a period, and then it must be true that $v_t^1 = v_t^2$, i.e. the value-equivalent tuples are not different).
- $SREL$ is the set of all snapshot relations.
- For every $n \in \{1, 2, 3, \dots\}$, $VREL_P(n)$ contains all the relations of $VREL_P$ that have n explicit attributes. Similarly, $NVREL_P(n)$ and $SREL(n)$ contain all the relations of $NVREL_P$ and $SREL$ respectively that have n explicit attributes.

To simplify the proofs in the rest of this chapter, I include the empty relation in all $VREL_P(n)$, $NVREL_P(n)$, $SREL(n)$, for $n = 1, 2, 3, \dots$.

5.2.4 The TSQL2 language

This section is an introduction to the features of TSQL2 that are used in this thesis.

SELECT statements

As noted in section 1.2.4, TSQL2 is an extension of SQL-92. Roughly speaking, SQL-92 queries (e.g. 5.3) consist of three clauses: a **SELECT**, a **FROM**, and a **WHERE** clause. (The term *SELECT statement* will be used to refer to the whole of a SQL-92 or TSQL2 query.)

⁴ Table 8.3 of [Snodgrass 95] implies that v_ε is the special “null” value. In SQL, null has several roles. Here, I assume that there is a special value v_ε whose only role is to denote the empty set.

```
(5.3)  SELECT DISTINCT sal.salary
        FROM salaries AS sal, managers AS mgr
        WHERE mgr.manager = 'J.Adams' AND sal.employee = mgr.managed
```

Assuming that *salaries* and *managers* are as below, (5.3) generates the third relation below.

<i>salaries</i>		<i>managers</i>		<i>(result)</i>
<i>employee</i>	<i>salary</i>	<i>manager</i>	<i>managed</i>	<i>salary</i>
<i>J.Adams</i>	17000	<i>J.Adams</i>	<i>G.Papas</i>	17000
<i>T.Smith</i>	18000	<i>J.Adams</i>	<i>B.Hunter</i>	14500
<i>G.Papas</i>	14500	<i>J.Adams</i>	<i>J.Adams</i>	
<i>B.Hunter</i>	17000	<i>T.Smith</i>	<i>K.Kofen</i>	
<i>K.Kofen</i>	16000	<i>T.Smith</i>	<i>T.Smith</i>	

(5.3) generates a snapshot one-attribute relation that contains the salaries of all employees managed by J.Adams. The FROM clause of (5.3) shows that the query operates on the *salaries* and *managers* relations. *sal* and *mgr* are *correlation names*. They can be thought of as tuple-variables ranging over the tuples of *salaries* and *managers* respectively. The (optional) WHERE clause imposes restrictions on the possible combinations of tuple-values of *sal* and *mgr*. In every combination, the *manager* value of *mgr* must be *J.Adams*, and the *managed* value of *mgr* must be the same as the *employee* value of *sal*. For example, $\langle J.Adams, G.Papas \rangle$ and $\langle G.Papas, 14500 \rangle$ is an acceptable combination of *mgr* and *sal* values respectively, while $\langle J.Adams, G.Papas \rangle$ and $\langle B.Hunter, 17000 \rangle$ is not.

In SQL-92 (and TSQL2), correlation names are optional, and relation names can be used to refer to attribute values. In (5.3), for example, one could omit AS *mgr*, and replace *mgr.manager* and *mgr.managed* by *managers.manager* and *managers.managed*. To simplify the definitions of section 5.4 below, I treat correlation names as mandatory, and I do not allow relation names to be used to refer to attribute values.

The SELECT clause specifies the contents of the resulting relation. In (5.3), it specifies that the resulting relation should have only one attribute, *salary*, and that for each acceptable combination of *sal* and *mgr* values, the corresponding tuple of the resulting relation should contain the *salary* value of *sal*'s tuple. The DISTINCT in (5.3) causes duplicates of tuples to be removed from the resulting relation. Without the DISTINCT duplicates are not removed. The result of (5.3) would contain two identical tuples $\langle 17000 \rangle$, deriving from the tuples for J.Adams and B.Hunter in *salaries*. This is against the set-theoretic definition of relations of sections 5.2.1 and 5.2.3 (relations

were defined to be *sets* of tuples, and hence cannot contain duplicates.) To ensure that relations contain no duplicates, in this thesis **SELECT** statements always have a **DISTINCT** in their **SELECT** clauses.

TSQL2 allows **SELECT** statements to operate on valid-time relations as well. A **SNAPSHOT** keyword in the **SELECT** statement indicates that the resulting relation is snapshot. When the resulting relation is valid-time, an additional **VALID** clause is present. In the latter case, the **SELECT** clause specifies the values of the explicit attributes of the resulting relation, while the **VALID** clause specifies the time-stamps of the resulting tuples. Assuming, for example, that *val_salaries* is as in (5.1), (5.4) returns (5.5).

(5.4) **SELECT DISTINCT sal.employee, sal.salary**
VALID PERIOD(BEGIN(VALID(sal)), END(VALID(sal)))
FROM val_salaries AS sal

(5.5)

<i>employee</i>	<i>salary</i>	
<i>J.Adams</i>	17000	[1/1/92, 30/10/94]
<i>J.Adams</i>	18000	[13/6/92, <i>now</i>]
<i>T.Smith</i>	21000	[15/6/92, <i>now</i>]

The **VALID** keyword is used both to start a **VALID**-clause (a clause that specifies the time-stamps of the resulting relation) and to refer to the time-stamp of the tuple-value of a correlation name. In (5.4), **VALID(sal)** refers to the time-stamp of **sal**'s tuple (i.e. to the time-stamp of a tuple from *val_salaries*). **BEGIN(VALID(sal))** refers to the first chronon of the temporal element represented by that time-stamp, and **END(VALID(sal))** to the last chronon of that temporal element.⁵ The **PERIOD** function generates a period that starts at the chronon of its argument, and ends at the chronon of its second argument. Hence, each time-stamp of (5.5) represents a period that starts/ends at the earliest/latest chronon of the temporal element of the corresponding time-stamp of *val_salaries*.

Literals

TSQL2 provides **PERIOD** literals, **INTERVAL** literals, and **TIMESTAMP** literals (the use of “**TIMESTAMP**” in this case is unfortunate; these literals specify time-points, not time-stamps of valid-time relations, which denote temporal-elements). For example, **PERIOD**

⁵ Section 30.5 of [Snodgrass 95] allows **BEGIN** and **END** to be used only with periods. I see no reason for this limitation. I allow **BEGIN** and **END** to be used with any temporal element.

'[March 3, 1995 - March 20, 1995]' is a literal that specifies a period at the granularity of days. If chronons are finer than days, the assumption in TSQL2 is that the exact chronons within March 3 and March 20 where the period starts and ends are unknown (section 5.2.2). In this thesis, PERIOD literals that refer to granularities other than that of chronons are abbreviations for literals that refer to the granularity of chronons. The denoted period contains all the chronons that fall within the granules specified by the literal. For example, if chronons correspond to minutes, PERIOD '[March 3, 1995 - March 20, 1995]' is an abbreviation for PERIOD '[00:00 March 3, 1995 - 23:59 March 20, 1995]'.

TSQL2 supports multiple calendars (e.g. Gregorian, Julian, lunar calendar; see chapter 7 of [Snodgrass 95]). The strings that can appear between the quotes of PERIOD literals (e.g. '[March 3, 1995 - March 20, 1995]', '(3/4/95 - 20/4/95)') depend on the available calendars and the selected formatting options (see chapter 7 of [Snodgrass 95]). The convention seems to be that the boundaries are separated by a dash, and that the first and last characters of the quoted string are square or round brackets, depending on whether the boundaries are to be included or not. I also assume that PERIOD 'today' can be used (provided that chronons are at least as fine as days) to refer to the period that covers all the chronons of the present day. (There are other TSQL2 expressions that can be used to refer to the current day, but I would have to discuss TSQL2 granularity-conversion commands to explain these. Assuming that PERIOD 'today' is available allows me to avoid these commands.)

TIMESTAMP literals specify chronons. Only the following special TIMESTAMP literals are used in this thesis: TIMESTAMP 'beginning', TIMESTAMP 'forever', TIMESTAMP 'now'. These refer to the beginning of time, the end of time, and the present chronon.

An example of an INTERVAL literal is INTERVAL '5' DAY, which specifies a duration of five consecutive day-granules. The available granularities depend on the calendars that are active. The granularities of years, months, days, hours, minutes, and seconds are supported by default. Intervals can also be used to shift periods or chronons towards the past or the future. For example, PERIOD '[1991 - 1995]' + INTERVAL '1' YEAR is the same as PERIOD '[1992 - 1996]'. If chronons correspond to minutes, PERIOD(TIMESTAMP 'beginning', TIMESTAMP 'now' - INTERVAL '1' MINUTE) specifies the period that covers all the chronons from the beginning of time up to (but not including) the current chronon.

Other TSQL2 functions and predicates

The `INTERSECT` function computes the intersection of two sets of chronons.⁶ For example, `INTERSECT(PERIOD 'May 1, 1995 - May 10, 1995', PERIOD 'May 3, 1995 - May 15, 1995')` is the same as `PERIOD 'May 3, 1995 - May 10, 1995'`. If the intersection is the empty set, `INTERSECT` returns v_ϵ (section 5.2.3).

The `CONTAINS` predicate checks if a chronon belongs to a set of chronons. For example, if `val_salaries` is as in (5.1), (5.6) generates a snapshot relation showing the current salary of each employee. `CONTAINS` can also be used to check if a set of chronons is a subset of another set of chronons.⁷

```
(5.6)  SELECT DISTINCT SNAPSHOT sal.employee, sal.salary
        FROM val_salaries AS sal
        WHERE VALID(sal) CONTAINS TIMESTAMP 'now'
```

The `PRECEDES` predicate checks if a chronon or set of chronons strictly precedes another chronon or set of chronons. Section 8.3.6 of [Snodgrass 95] specifies the semantics of `PRECEDES` only in cases where its arguments are chronons or periods. I assume that `expr1 PRECEDES expr2` is true, iff the chronon of `expr1` (if `expr1` specifies a single chronon) or all the chronons of `expr1` (if `expr1` specifies a set of chronons) strictly precede the chronon of `expr2` (if `expr2` specifies a single chronon) or all the chronons of `expr2` (if `expr2` specifies a set of chronons). For example, `PERIOD '1/6/95 - 21/6/95' PRECEDES PERIOD '24/6/95 - 30/6/95'` is true, but `PERIOD '1/6/95 - 21/6/95' PRECEDES PERIOD '19/6/95 - 30/6/95'` is not.

Embedded SELECT statements

TSQL2 (and SQL-92) allow embedded `SELECT` statements to be used in the `FROM` clause, in the same way that relation names are used (e.g. (5.7)).

⁶ Section 8.3.3 of [Snodgrass 95] requires both arguments of `INTERSECT` to denote periods, but section 30.14 allows the arguments of `INTERSECT` to denote temporal elements. I follow the latter. I also allow the arguments of `INTERSECT` to denote the empty set.

⁷ Table 8.7 in section 8.3.6 and additional syntax rule 3 in section 32.4 of [Snodgrass 95] allow the arguments of `CONTAINS` to denote periods but not generally temporal elements. Table 32.1 in section 32.4 of [Snodgrass 95], however, allows the arguments of `CONTAINS` to denote temporal elements. I follow the latter. I also allow the arguments of `CONTAINS` to denote the empty set. The same comments apply in the case of `PRECEDES`.

```
(5.7)  SELECT DISTINCT SNAPSHOT sal2.salary
        FROM (SELECT DISTINCT sal1.salary
              VALID VALID(sal1)
              FROM val_salaries AS sal1
              ) AS sal2
        WHERE sal2.salary > 17500
```

Assuming that *val_salaries* is as in (5.1), the embedded **SELECT** statement above simply drops the *employee* attribute of *val_salaries*, generating (5.8). *sal2* ranges over the tuples of (5.8). (5.7) generates a relation that is the same as (5.8), except that tuples whose *salary* values are not greater than 17500 are dropped.

(5.8)

<i>salary</i>	
17000	[1/1/92, 12/6/92] \cup [8/5/94, 30/10/94]
18000	[13/6/92, 7/5/94] \cup [31/10/94, <i>now</i>]
21000	[15/6/92, <i>now</i>]

Partitioning units

In TSQL2, relation names and embedded **SELECT** statements in the **FROM** clause can be followed by *partitioning units*.⁸ TSQL2 currently provides two partitioning units: (PERIOD) and (INSTANT) (see section 30.3 and chapter 12 of [Snodgrass 95]). (INSTANT) is not used in this thesis. Previous TSQL2 versions (e.g. the September 1994 version of chapter 12 of [Snodgrass 95]) provided an additional (ELEMENT). For reasons explained below, (ELEMENT) is still used in this thesis.

(ELEMENT) merges value-equivalent tuples.⁹ For example, if *rel1* is the relation of (5.9), (5.10) generates the coalesced relation of (5.11).

(5.9)

<i>rel1</i>		
<i>employee</i>	<i>salary</i>	
<i>J.Adams</i>	17000	[1986, 1988]
<i>J.Adams</i>	17000	[1987, 1990]
<i>J.Adams</i>	17000	[1992, 1994]
<i>G.Papas</i>	14500	[1988, 1990]
<i>G.Papas</i>	14500	[1990, 1992]

⁸ Section 30.3 of [Snodgrass 95] allows relation names but not embedded **SELECT** statements to be followed by partitioning units in **FROM** clauses. [Snodgrass *et al.* 94b] (queries Q.1.2.2, Q.1.2.5, Q.1.7.6), however, shows **SELECT** statements embedded in **FROM** clauses and followed by partitioning units. I follow [Snodgrass *et al.* 94b].

⁹ The semantics of (ELEMENT) was never clear. The discussion here reflects my understanding of the September 1994 TSQL2 documentation, and the semantics that is assigned to (ELEMENT) in this thesis.

(5.10) `SELECT DISTINCT r1.employee, r1.salary`
`VALID VALID(r1)`
`FROM rel1(ELEMENT) AS r1`

(5.11)

<i>employee</i>	<i>salary</i>	
<i>J.Adams</i>	17000	[1986, 1990] \cup [1992, 1994]
<i>G.Papas</i>	14500	[1988, 1992]

The effect of (ELEMENT) on a valid-time relation r is captured by the *coalesce* function:

$$\text{coalesce}(r) \stackrel{\text{def}}{=} \{ \langle v_1, \dots, v_n; v_t \rangle \mid \langle v_1, \dots, v_n; v'_t \rangle \in r \text{ and} \\ f_D(v_t) = \bigcup_{\langle v_1, \dots, v_n; v''_t \rangle \in r} f_D(v''_t) \}$$

(ELEMENT) has no effect on already coalesced valid-time relations. Hence, in the BCDM version of [Snodgrass 95], where all valid-time relations are coalesced, (ELEMENT) is redundant (and this is probably why it was dropped). In this thesis, valid-time relations are not necessarily coalesced (section 5.2.3), and (ELEMENT) plays an important role.

(PERIOD) intuitively breaks each tuple of a valid-time relation into value-equivalent tuples, each corresponding to a maximal period of the temporal element of the original time-stamp. Assuming, for example, that *rel2* is the relation of (5.11), (5.12) generates (5.13).

(5.12) `SELECT DISTINCT r2.employee, r2.salary`
`VALID VALID(r2)`
`FROM rel2(PERIOD) AS r2`

(5.13)

<i>employee</i>	<i>salary</i>	
<i>J.Adams</i>	17000	[1986, 1990]
<i>J.Adams</i>	17000	[1992, 1994]
<i>G.Papas</i>	14500	[1988, 1992]

As the example shows, (PERIOD) may generate non-coalesced relations. This is mysterious in the BCDM version of [Snodgrass 95], where non-coalesced valid-time relations are not allowed. The assumption seems to be that although non-coalesced valid-time relations are not allowed, during the execution of `SELECT` statements temporary non-coalesced valid-time relations may be generated. Any resulting valid-time relations, however, are coalesced automatically at the end of the statement's execution. (5.13) would be coalesced automatically at the end of the execution of (5.12) (cancelling, in this particular example, the effect of (PERIOD)). In this thesis, no automatic coalescing takes place, and the result of (5.12) is (5.13).

To preserve the spirit of (PERIOD) in the BCDM version of this thesis where valid-time relations are not necessarily coalesced, I assume that (PERIOD) operates on a coalesced copy of the original relation. Intuitively, (PERIOD) first causes (5.9) to become (5.11), and then generates (5.13). The effect of (PERIOD) on a valid-time relation r is captured by the *pcoalesce* function:

$$pcoalesce(r) \stackrel{def}{=} \{ \langle v_1, \dots, v_n; v_t \rangle \mid \langle v_1, \dots, v_n; v'_t \rangle \in coalesce(r) \text{ and } f_D(v_t) \in mxlpers(f_D(v'_t)) \}$$

5.3 Modifications of TSQL2

This thesis adopts some modifications of TSQL2. Some of the modifications were mentioned in section 5.2. The main of those were:

- The requirement that all valid-time relations must be coalesced was dropped.
- The distinction between state and event valid-time relations was abandoned.
- (ELEMENT) was re-introduced.
- The semantics of (PERIOD) was enhanced, to reflect the fact that in this thesis valid-time relations are not necessarily coalesced.
- All periods and temporal elements are specified at the granularity of chronons. Literals referring to other granularities are used as abbreviations for literals that refer to the granularity of chronons.

This section describes the remaining TSQL2 modifications of this thesis.

5.3.1 Referring to attributes by number

In TSQL2 (and SQL-92) explicit attributes are referred to by their names. In (5.14), for example, `sal.salary` refers to the *salary* attribute of *val_salaries*.

```
(5.14)  SELECT DISTINCT sal.salary
        VALID VALID(sal)
        FROM val_salaries AS sal
```


In the TSQL2 version of this thesis, explicit attributes are referred to by number, with numbers corresponding to the order in which the attributes appear in the relation schema (section 5.2.1). For example, if the relation schema of *val_salaries* is $\langle employee, salary \rangle$, *employee* is the first explicit attribute and *salary* the second one. (5.15) would be used instead of (5.14). To refer to the implicit attribute, one still uses *VALID* (e.g. *VALID(sal)*).

```
(5.15)  SELECT DISTINCT sal.2
        VALID VALID(sal)
        FROM salaries AS sal
```

Referring to explicit attributes by number simplifies the TOP to TSQL2 translation, because this way there is no need to keep track of the attribute names of the various relations.

5.3.2 (SUBPERIOD) and (NOSUBPERIOD)

Two new partitioning units, (SUBPERIOD) and (NOSUBPERIOD), were introduced for the purposes of this thesis. (SUBPERIOD) is designed to be used with relations from *VREL_P* (section 5.2.3). The effect of (SUBPERIOD) on a relation *r* is captured by the *subperiod* function:

$$subperiod(r) \stackrel{def}{=} \{ \langle v_1, \dots, v_n; v_t \rangle \mid \langle v_1, \dots, v_n; v'_t \rangle \in r \text{ and } f_D(v_t) \sqsubseteq f_D(v'_t) \}$$

For each tuple $\langle v_1, \dots, v_n; v'_t \rangle \in r$, the resulting relation contains many value-equivalent tuples of the form $\langle v_1, \dots, v_n; v_t \rangle$, one for each period $f_D(v_t)$ that is a subperiod of $f_D(v'_t)$. Assuming, for example, that chronons correspond to years, and that *rel* is the relation of (5.16), (5.17) returns the relation of (5.18).

(5.16)

<i>J.Adams</i>	17000	[1992, 1993]
<i>G.Papas</i>	14500	[1988, 1990]
<i>G.Papas</i>	14500	[1990, 1991]

```
(5.17)  SELECT DISTINCT r.1, r.2
        VALID VALID(r)
        FROM rel(SUBPERIOD) AS r
```

(5.18)

<i>J.Adams</i>	17000	[1992, 1993]
<i>J.Adams</i>	17000	[1992, 1992]
<i>J.Adams</i>	17000	[1993, 1993]
<i>G.Papas</i>	14500	[1988, 1990]
<i>G.Papas</i>	14500	[1988, 1988]
<i>G.Papas</i>	14500	[1988, 1989]
<i>G.Papas</i>	14500	[1989, 1989]
<i>G.Papas</i>	14500	[1989, 1990]
<i>G.Papas</i>	14500	[1990, 1990]
<i>G.Papas</i>	14500	[1990, 1991]
<i>G.Papas</i>	14500	[1991, 1991]

The first three tuples of (5.18) correspond to the first tuple of (5.16). The following six tuples correspond to the first tuple of *G.Papas* in (5.16). The remaining tuples of (5.18) derive from the second tuple of *G.Papas* in (5.16) (the tuple for the subperiod [1990, 1990] has already been included in (5.18)). Notice that (SUBPERIOD) does not coalesce the original relation before generating the result (this is why there is no tuple for *G.Papas* time-stamped by [1988, 1991] in (5.18)).

Obviously, the cardinality of the resulting relations can be very large (especially if chronons are very fine, e.g. seconds). The cardinality, however, is never infinite (assuming that the cardinality of the original relation is finite): given that time is discrete, linear, and bounded, any period p is a finite set of chronons, and there is at most a finite number of periods (convex sets of chronons) that are subperiods (subsets) of p ; hence, for any tuple in the original relation whose time-stamp represents a period p , there will be at most a finite number of tuples in the resulting relation whose time-stamps represent subperiods of p . It remains, of course, to be examined if (SUBPERIOD) can be supported efficiently in DBMSs. It is obviously very inefficient to store (or print) individually all the tuples of the resulting relation. A more space-efficient encoding of the resulting relation is needed. I have not explored this issue.

Roughly speaking, (SUBPERIOD) is needed because during the TOP to TSQL2 translation every TOP formula is mapped to a valid-time relation whose time-stamps denote the event-time periods where the formula is true. Some (but not all) formulae are homogeneous (section 3.6). For these formulae we need to ensure that if the valid-time relation contains a tuple for an event-time et , it also contains tuples for all the subperiods of et . This will become clearer in section 5.11.

(NOSUBPERIOD) is roughly speaking used when the effect of (SUBPERIOD) needs to be cancelled. (NOSUBPERIOD) is designed to be used with relations from $VREL_P$. It eliminates any tuple $\langle v_1, \dots, v_n; v_t \rangle$, for which there is a value-equivalent tuple $\langle v_1, \dots, v_n; v'_t \rangle$, such that $f_D(v_t) \sqsubset f_D(v'_t)$. The effect of (NOSUBPERIOD) on a valid-time relation r is captured by the *nosubperiod* function:

$$\text{nosubperiod}(r) \stackrel{\text{def}}{=} \{ \langle v_1, \dots, v_n; v_t \rangle \in r \mid \text{there is no } \langle v_1, \dots, v_n; v'_t \rangle \in r \\ \text{such that } f_D(v_t) \sqsubset f_D(v'_t) \}$$

Applying (NOSUBPERIOD) to (5.18) generates (5.19).

(5.19)

<i>J.Adams</i>	17000	[1992, 1993]
<i>G.Papas</i>	14500	[1988, 1990]
<i>G.Papas</i>	14500	[1990, 1991]

Although (SUBPERIOD) and (NOSUBPERIOD) are designed to be used (and in practice will always be used) with relations from $VREL_P$, I allow (SUBPERIOD) and (NOSUBPERIOD) to be used with any valid-time relation. In the proofs of appendix A, this saves me having to prove that the original relation is an element of $VREL_P$ whenever (SUBPERIOD) and (NOSUBPERIOD) are used.

5.3.3 Calendric relations

As mentioned in section 5.2.4, TSQL2 supports multiple calendars. Roughly speaking, a TSQL2 calendar describes a system that people use to measure time (Gregorian calendar, Julian calendar, etc.). TSQL2 calendars also specify the meanings of strings within the quotes of temporal literals, and the available granularities. According to section 3.2 of [Snodgrass 95], TSQL2 calendars are defined by the database administrator, the DBMS vendor, or third parties. In this thesis, I assume that TSQL2 calendars can also provide *calendric relations*. Calendric relations behave like ordinary relations in the database, except that they are defined by the creator of the TSQL2 calendar, and cannot be updated.

The exact purpose and contents of each calendric relation are left to the calendar creator. I assume, however, that a calendric relation provides information about the time-measuring system of the corresponding TSQL2 calendar.¹⁰ The Gregorian TSQL2

¹⁰ Future work could establish a more systematic link between calendric relations and TSQL2 calendars. For example, calendric relations could be required to reflect (as a minimum) the lattice that shows how the granularities of the calendar relate to each other (section 5.2.2).

calendar could, for example, provide the calendric valid-time relation *gregorian* below. (I assume here that chronons are finer than minutes.)

<i>gregorian</i>						
<i>year</i>	<i>month</i>	<i>dnum</i>	<i>dname</i>	<i>hour</i>	<i>minute</i>	
...
1994	<i>Sept</i>	4	<i>Sun</i>	00	00	$\{c_{n_1}, \dots, c_{n_2}\}$
1994	<i>Sept</i>	4	<i>Sun</i>	00	01	$\{c_{n_3}, \dots, c_{n_4}\}$
...
1995	<i>Dec</i>	5	<i>Tue</i>	21	35	$\{c_{n_5}, \dots, c_{n_6}\}$
...

The relation above means that the first minute (00:00) of September 4th 1994 (which was a Sunday) covers exactly the period that starts at the chronon c_{n_1} and ends at the chronon c_{n_2} . Similarly, the period that starts at c_{n_3} and ends at c_{n_4} is the second minute (00:01) of September 4th 1994. Of course, the cardinality of *gregorian* is very large, though not infinite (time in TSQL2 is bounded, and hence there is at most a finite number of minute-granules). It is important, however, to realise that although *gregorian* behaves like a normal relation in the database, it does not need to be physically present in the database. Its tuples could be computed dynamically, whenever they are needed, using some algorithm specified by the TSQL2 calendar. Other calendric relations may list the periods that correspond to seasons (spring-periods, summer-periods, etc.), special days (e.g. Easter days), etc.

Calendric relations like *gregorian* can be used to construct relations that represent the periods of partitionings. (5.20), for example, constructs a one-attribute snapshot relation, that contains all the time-stamps of *gregorian* that correspond to 21:36-minutes. The resulting relation represents all the periods of the partitioning of 21:36-minutes.

```
(5.20)  SELECT DISTINCT SNAPSHOT VALID(greg)
        FROM gregorian AS greg
        WHERE greg.5 = 21 AND greg.6 = 36
```

Similarly, (5.21) generates a one-attribute snapshot relation that represents the periods of the partitioning of Sunday-periods. The embedded **SELECT** statement generates a valid-time relation of one explicit attribute (whose value is *Sun* in all tuples). The time-stamps of this relation are all the time-stamps of *gregorian* that correspond to Sundays (there are many tuples for each Sunday). The (PERIOD) coalesces tuples that correspond to the same Sunday, leading to a single period-denoting time-stamp for

each Sunday. These time-stamps become the attribute values of the relation generated by the overall (5.21).

```
(5.21)  SELECT DISTINCT SNAPSHOT VALID(greg2)
        FROM (SELECT DISTINCT greg1.4
              VALID VALID(greg1)
              FROM gregorian AS greg1
              WHERE greg1.4 = 'Sun'
              )(PERIOD) AS greg2
```

In [Androutsopoulos *et al.* 95a] we argue that calendric relations constitute a generally useful addition to TSQL2, and that unless appropriate calendric relations are available, it is not possible to formulate TSQL2 queries for questions involving existential or universal quantification or counts over day-names, month names, season-names, etc. (e.g. (5.22) – (5.24)).

(5.22) Which technicians were at some site on a Sunday?

(5.23) Which technician was at Glasgow Central on every Monday in 1994?

(5.24) On how many Sundays was J.Adams at Glasgow Central in 1994?

5.3.4 The INTERVAL function

TSQL2 provides a function `INTERVAL` that accepts a period-denoting expression as its argument, and returns an interval reflecting the duration of the period. The assumption seems to be that the resulting interval is specified at whatever granularity the period is specified. For example, `INTERVAL(PERIOD '1/12/95 - 3/12/95')` is the same as `INTERVAL '3' DAY`. In this thesis, all periods are specified at the granularity of chronons, and if chronons correspond to minutes, `PERIOD '1/12/95 - 3/12/95'` is an abbreviation for `PERIOD '00:00 1/12/95 - 23:59 3/12/95'` (sections 5.2.2 and 5.2.4). Hence, the results of `INTERVAL` are always specified at the granularity of chronons. When translating from TOP to TSQL2, however, there are cases where we want the results of `INTERVAL` to be specified at other granularities.

This could be achieved by converting the results of `INTERVAL` to the desired granularities. The TSQL2 mechanisms for converting intervals from one granularity to another, however, are very obscure (see section 19.4.6 of [Snodgrass 95]). To avoid these mechanisms, I introduce an additional version of the `INTERVAL` function. If $expr_1$ is a TSQL2 expression that specifies a period p , and $expr_2$ is the TSQL2 name (e.g.

DAY, MONTH) of a granularity G , then `INTERVAL(expr1, expr2)` specifies an interval of n granules (periods) of G , where n is as follows. If there are k consecutive granules $g_1, g_2, g_3, \dots, g_k$ in G such that $g_1 \cup g_2 \cup g_3 \cup \dots \cup g_k = p$, then $n = k$. Otherwise, $n = 0$. For example, `INTERVAL(PERIOD '[May 5, 1995 - May 6, 1995]', DAY)` is the same as `INTERVAL '2' DAY`, because the period covers exactly 2 consecutive day-granules. Similarly, `INTERVAL(PERIOD '[May 1, 1995 - June 30, 1995]', MONTH)` is the same as `INTERVAL '2' MONTH`, because the period covers exactly two consecutive month-granules. In contrast, `INTERVAL(PERIOD '[May 1, 1995 - June 15, 1995]', MONTH)` is the same as `INTERVAL '0' MONTH` (zero duration), because there is no union of consecutive month-granules that covers exactly the period of `PERIOD '[May 1, 1995 - June 15, 1995]'`.

5.3.5 Correlation names used in the same FROM clause where they are defined

The syntax of TSQL2 (and SQL-92) does not allow a correlation name to be used in a `SELECT` statement that is embedded in the same `FROM` clause that defines the correlation name. For example, (5.25) is not allowed, because the embedded `SELECT` statement uses `r1`, which is defined by the same `FROM` clause that contains the embedded `SELECT` statement.

```
(5.25)  SELECT ...
        VALID VALID(r1)
        FROM rel1 AS r1,
           (SELECT ...
            VALID VALID(r2)
            FROM rel2 AS r2
            WHERE VALID(r1) CONTAINS VALID(r2)
           ) AS r3
        WHERE ...
```

By *definition of a correlation name* α , I mean the expression “AS α ” that associates α with a relation. For example, in (5.25) the definition of `r1` is the “AS `r1`”.¹¹ A correlation name α is *defined by a FROM clause* ξ , if ξ contains the definition of α , and this definition is not within a `SELECT` statement which is embedded in ξ . For example, in (5.25) the `r2` is defined by the “FROM `rel2 AS r2`” clause, not by the “FROM `rel1 AS`

¹¹ In `SELECT` statements that contain other embedded `SELECT` statements, multiple definitions of the same correlation name may be present (there are rules that determine the scope of each definition). We do not need to worry about such cases, however, because the generated TSQL2 code of this chapter never contains multiple definitions of the same correlation name.

`r1, (...) AS r3`” clause.

In this thesis, I allow a correlation name to be used in a `SELECT` statement that is embedded in the same `FROM` clause that defines the correlation name, provided that the definition of the correlation name precedes the embedded `SELECT` statement. (5.25) is acceptable, because the definition of `r1` precedes the embedded `SELECT` statement where `r1` is used. In contrast, (5.26) is not acceptable, because the definition of `r1` follows the embedded `SELECT` statement where `r1` is used.

```
(5.26)  SELECT ...
        VALID VALID(r1)
        FROM (SELECT ...
              VALID VALID(r2)
              FROM rel2 AS r2
              WHERE VALID(r1) CONTAINS VALID(r2)
              ) AS r3,
          rel1 AS r1
        WHERE ...
```

The intended semantics of statements like (5.25) should be easy to see: when evaluating the embedded `SELECT` statement, `VALID(r1)` should represent the time-stamp of a tuple from `rel1`. The restriction that the definition of the correlation name must precede the embedded `SELECT` is imposed to make this modification easier to implement.

The modification of this section is used in the TOP to TSQL2 translation rules for *At* $[\phi_1, \phi_2]$, *Before* $[\phi_1, \phi_2]$, and *After* $[\phi_1, \phi_2]$ (section 5.11 below and appendix A).

5.3.6 Equality checks and different domains

Using the equality predicate (=) with expressions that refer to values from different domains often causes the TSQL2 (or SQL-92) interpreter to report an error. If, for example, the domain of the first explicit attribute of *rel* is the set of all integers, `r.1` in (5.27) stands for an integer. TSQL2 (and SQL-92) does not allow integers to be compared to strings (e.g. “J.Adams”). Consequently, (5.27) would be rejected, and an error message would be generated.

```
(5.27)  SELECT DISTINCT SNAPSHOT r.2
        FROM rel AS r
        WHERE r.1 = 'J.Adams'
```

In other cases (e.g. if a real number is compared to an integer), type conversions take place before the comparison. To by-pass uninteresting details, in this thesis I assume

that no type conversions occur when “=” is used. The equality predicate is satisfied iff both of its arguments refer to the same element of D (universal domain). No error occurs if the arguments refer to values from different domains. In the example of (5.27), $r.1 = 'J.Adams'$ is not satisfied, because $r.1$ refers to an integer in D , $'J.Adams'$ to a string in D , and integers are different from strings. Consequently, in the TSQL2 version of this thesis (5.27) generates the empty relation (no errors occur).

5.3.7 Other minor changes

TSQL2 does not allow partitioning units to follow **SELECT** statements that are not embedded into other **SELECT** statements. For example, (5.28) on its own is not acceptable.

```
(5.28)  (SELECT DISTINCT r1.1, r1.2
        VALID VALID(r1)
        FROM rel AS r1
        )(PERIOD)
```

SELECT statements like (5.28) can be easily made acceptable by embedding them into another **SELECT** statement (e.g. (5.29)).

```
(5.29)  SELECT DISTINCT r2.1, r2.2
        VALID VALID(r2)
        FROM (SELECT DISTINCT r1.1, r1.2
              VALID VALID(r1)
              FROM rel AS r1
              )(PERIOD) AS r2
```

For simplicity, I allow stand-alone statements like (5.28). I assume that (5.28) generates the same relation as (5.29). I also allow stand-alone **SELECT** statements enclosed in brackets (e.g. (5.30)). I assume that the enclosing brackets are simply ignored.

```
(5.30)  (SELECT DISTINCT r1.1, r1.2
        VALID VALID(r1)
        FROM rel AS r1
        )
```

5.4 Additional TSQL2 terminology

This section defines some additional terminology, that is used to formulate and prove the correctness of the TOP to TSQL2 translation.

Column reference: A *column reference* is an expression of the form $\alpha.i$ or $\text{VALID}(\alpha)$, where α is a correlation name and $i \in \{1, 2, 3, \dots\}$ (e.g. `sal.2`, `VALID(sal)`).

Binding context: A SELECT statement Σ is a *binding context* for a column reference $\alpha.i$ or $\text{VALID}(\alpha)$ iff:

- the column reference is part of Σ ,
- α is defined (in the sense of section 5.3.5) by the topmost FROM clause of Σ , and
- the column reference is not in the topmost FROM clause of Σ ; or it is in the topmost FROM clause of Σ , but the definition of α precedes the column reference.

By *topmost FROM clause of Σ* I mean the (single) FROM clause of Σ that does not appear in any SELECT statement embedded in Σ (e.g. the topmost FROM clause of (5.32) is the “FROM `tab1 AS r1`, (...) AS `r3`”). We will often have to distinguish between individual *occurrences* of column references. For example, (5.31) is a binding context for the occurrence of `VALID(r1)` in the `VALID` clause, because that occurrence is part of (5.31), `r1` is defined by the topmost FROM clause of (5.31), and the occurrence of `VALID(r1)` is not in the topmost FROM clause of (5.31). (5.31), however, is *not* a binding context for the occurrence of `VALID(r1)` in the embedded SELECT statement of (5.31), because that occurrence is in the topmost FROM clause, and it does not follow the definition of `r1`.

```
(5.31)  SELECT DISTINCT r1.1, r3.2
        VALID VALID(r1)
        FROM (SELECT DISTINCT SNAPSHOT r2.1, r2.2
              FROM tab2 AS r2
              WHERE VALID(r2) CONTAINS VALID(r1)
              ) AS r3,
          tab1 AS r1
        WHERE r1.1 = 'J.Adams'
```

In contrast, (5.32) *is* a binding context for the `VALID(r1)` in the embedded SELECT, because the definition of `r1` precedes that occurrence of `VALID(r1)`.

```

(5.32)  SELECT DISTINCT r1.1, r3.2
        VALID VALID(r1)
        FROM tab1 AS r1,
             (SELECT DISTINCT SNAPSHOT r2.1, r2.2
              FROM tab2 AS r2
              WHERE VALID(r2) CONTAINS VALID(r1)
              ) AS r3
        WHERE r1.1 = 'J.Adams'

```

In both (5.31) and (5.32), the overall `SELECT` statement is not a binding context for `r2.1`, `r2.2`, and `VALID(r2)`, because `r2` is not defined by the topmost `FROM` clause of the overall `SELECT` statement. The embedded `SELECT` statement of (5.31) and (5.32), however, *is* a binding context for `r2.1`, `r2.2`, and `VALID(r2)`.

Free column reference: A column reference $\alpha.i$ or `VALID(α)` is a *free column reference* in a TSQL2 expression ξ , iff:

- the column reference is part of ξ , and
- there is no `SELECT` statement in ξ (possibly being the whole ξ) that is a binding context for the column reference.

The `VALID(r1)` in the embedded `SELECT` statement of (5.31) is free in (5.31), because there is no binding context for that occurrence in (5.31). In contrast, the `VALID(r1)` in the `VALID` clause of (5.31) is not free in (5.31), because (5.31) is a binding context for that occurrence. The `VALID(r2)` of (5.31) is not free in (5.31), because the embedded `SELECT` statement is a binding context for `VALID(r2)`.

A correlation name α *has a free column reference in* a TSQL2 expression ξ , iff there is a free column reference $\alpha.i$ or `VALID(α)` in ξ . For every TSQL2 expression ξ , $FCN(\xi)$ is the set of all correlation names that have a free column reference in ξ . For example, if ξ is (5.31), $FCN(\xi) = \{r1\}$ (the `VALID(r1)` of the embedded `SELECT` statement is free in (5.31)).

There must be no free column references in the overall `SELECT` statements that are submitted to the TSQL2 (or SQL-92) interpreter (though there may be free column references in their embedded `SELECT` statements). Hence, it is important to prove that there are no free column references in the overall `SELECT` statements generated by the TOP to TSQL2 translation.

Value expression: In TSQL2 (and SQL-92), *value expression* refers to expressions that normally evaluate to elements of D (universal domain). (The meaning of “normally” will be explained in following paragraphs.) For example, 'J.Adams', VALID(sal), and INTERSECT(PERIOD '[1993 - 1995]', PERIOD '[1994 - 1996]') are all value expressions.

Assignment to correlation names: An *assignment to correlation names* is a function g^{db} that maps every TSQL2 correlation name to a possible tuple of a snapshot or valid-time relation. G^{db} is the set of all assignments to correlation names

If α is a (particular) correlation name, $\langle v_1, v_2, \dots \rangle$ is a (particular) tuple of a snapshot or valid-time relation, and $g^{db} \in G^{db}$, $(g^{db})_{\langle v_1, v_2, \dots \rangle}^\alpha$ is the same as g^{db} , except that it assigns $\langle v_1, v_2, \dots \rangle$ to α . (For every other correlation name, the values of g^{db} and $(g^{db})_{\langle v_1, v_2, \dots \rangle}^\alpha$ are identical.)

eval: For every TSQL2 SELECT statement or value expression ξ , and every $st \in CHRONS$ and $g^{db} \in G^{db}$, $eval(st, \xi, g^{db})$ is the relation (if ξ is a SELECT statement) or the element of D (if ξ is a value expression) that is generated when the TSQL2 interpreter evaluates ξ in the following way:

- st is taken to be the current chronon.
- Every free column reference of the form $\alpha.i$ is treated as a value expression that evaluates to v_i , where v_i is the i -th attribute value in the tuple $g^{db}(\alpha)$.
- Every free column reference of the form VALID(α) is treated as a value expression that evaluates to v_t , where v_t is the time-stamp of $g^{db}(\alpha)$.

If ξ cannot be evaluated in this way (e.g. ξ contains a free column reference of the form $\alpha.4$, and $g^{db}(\alpha) = \langle v_1, v_2, v_3 \rangle$), $eval(st, \xi, g^{db})$ returns the special value *error*. (I assume that *error* $\notin D$.) A value expression ξ *normally* (but not always) evaluates to an element of D , because when errors arise $eval(st, \xi, g^{db}) = error \notin D$. If, however, $eval(st, \xi, g^{db}) \neq error$, $eval(st, \xi, g^{db}) \in D$.

Strictly speaking, *eval* should also have as its argument the database against which ξ is evaluated. For simplicity, I overlook this detail. Finally, if $FCN(\xi) = \emptyset$ (ξ contains

no free column references), $eval(st, \xi, g^{db})$ does not depend on g^{db} . In this case, I write simply $eval(st, \xi)$.

5.5 Modifications in TOP and additional TOP terminology

In the formulae generated by the English to TOP translation, each $Part[\sigma, \beta]$ is conjoined with a subformula that is (or contains another subformula) of the form $At[\beta, \phi]$, $Before[\beta, \phi]$, or $After[\beta, \phi]$ ($\sigma \in PARTS$, $\phi \in YNFORMS$, $\beta \in VARS$, and the β of $Part$ is the same as that of At , $Before$, or $After$). For example, (5.33) and (5.35) are mapped to (5.34) and (5.36). Also the reading of (5.37) where Monday is the time when the tank was empty (rather than a reference time; section 2.5.5) is mapped to (5.38).

(5.33) Tank 2 was empty on a Monday.

(5.34) $Part[monday^g, mon^v] \wedge At[mon^v, Past[e^v, empty(tank2)]]$

(5.35) On which Monday was tank 2 empty?

(5.36) $?mon^v Part[monday^g, mon^v] \wedge At[mon^v, Past[e^v, empty(tank2)]]$

(5.37) Tank 2 had been empty on a Monday.

(5.38) $Part[monday^g, mon^v] \wedge Past[e1^v, Perf[e2^v, At[mon^v, empty(tank2)]]]$

In this chapter, I use a slightly different version of TOP, where the $Part$ is merged with the corresponding At , $Before$, or $After$. For example, (5.34), (5.36), and (5.38) become (5.39), (5.40), and (5.41) respectively.

(5.39) $At[monday^g, mon^v, Past[e^v, empty(tank2)]]$

(5.40) $?mon^v At[monday^g, mon^v, Past[e^v, empty(tank2)]]$

(5.41) $Past[e1^v, Perf[e2^v, At[monday^g, mon^v, empty(tank2)]]]$

The semantics of $At[\sigma, \beta, \phi]$, $Before[\sigma, \beta, \phi]$, and $After[\sigma, \beta, \phi]$ follow (f is f_{gparts} if $\sigma \in GPARTS$, and f_{cparts} if $\sigma \in CPARTS$.)

- $\|At[\sigma, \beta, \phi]\|^{st, et, lt, g} = T$ iff $g(\beta) \in f(\sigma)$ and $\|\phi\|^{st, et, lt \cap g(\beta), g} = T$.
- $\|Before[\sigma, \beta, \phi]\|^{st, et, lt, g} = T$ iff $g(\beta) \in f(\sigma)$ and $\|\phi\|^{st, et, lt \cap [t_{first}, minpt(\|\beta\|^g)], g} = T$.

- $\|After[\sigma, \beta, \phi]\|^{st, et, lt, g} = T$ iff $g(\beta) \in f(\sigma)$ and $\|\phi\|^{st, et, lt \cap (maxpt(\|\beta\|^g), t_{last}), g} = T$.

In the TOP version of this chapter, $Part[\sigma, \beta]$, $At[\beta, \phi]$, $Before[\beta, \phi]$, and $After[\beta, \phi]$ ($\beta \in VARS$) are no longer yes/no formulae. $At[\kappa, \phi]$, $Before[\kappa, \phi]$, and $After[\kappa, \phi]$ ($\kappa \in CONS$), however, are still yes/no formulae.

The TOP version of chapter 3 is more convenient for the English to TOP mapping, while the version of this chapter simplifies the TOP to TSQL2 translation. In the prototype NLITDB, there is a converter between the module that translates from English to TOP and the TOP to TSQL2 translator. The module that translates from English to TOP maps (5.33), (5.35), and (5.37) to (5.34), (5.36), and (5.38) respectively. The converter turns (5.34), (5.36), and (5.38) into (5.39), (5.40), and (5.41), which are then passed to the TOP to TSQL2 translator.

The reader is reminded that the $Part[\sigma, \beta, \nu_{ord}]$ version of $Part$ is not used in the translation from English to TOP (section 4.3). Hence, only the $Part[\sigma, \beta]$ form of $Part$ is possible in formulae generated by the English to TOP translation. In the TOP version of this chapter, $Part$ operators of this form are merged with At , $Before$, or $After$ operators. Therefore, no $Part$ operators occur in the formulae that are passed to the TOP to TSQL2 translator. As with the At , $Before$, and $After$ of chapter 3 (section 3.2), in every $At[\sigma, \beta, \phi]$, $Before[\sigma, \beta, \phi]$, and $After[\sigma, \beta, \phi]$, I require β not to occur within ϕ . This is needed to prove the correctness of the TOP to TSQL2 translation.

To avoid complications in the TOP to TSQL2 translation, I require that in any $At[\kappa, \phi]$, $Before[\kappa, \phi]$, or $After[\kappa, \phi]$ ($\kappa \in CONS$, $\phi \in YNFORMS$) that is passed to the TOP to TSQL2 translator, $f_{cons}(\kappa) \in PERIODS$. (The definitions of section 3.10 are more liberal: they allow $f_{cons}(\kappa)$ not to belong to $PERIODS$, though if $f_{cons}(\kappa) \notin PERIODS$, the denotation of $At[\kappa, \phi]$, $Before[\kappa, \phi]$, or $After[\kappa, \phi]$ is always F .) In practice, formulae generated by the English to TOP mapping never violate this constraint.

For every $\phi \in YNFORMS$, $\lceil \phi \rceil$ (pronounced “corners ϕ ”) is the tuple $\langle \tau_1, \tau_2, \tau_3, \dots, \tau_n \rangle$, where τ_1, \dots, τ_n are all the constants that are used as arguments of predicates in ϕ , and all the variables that occur in ϕ , in the same order (from left to right) they appear in ϕ . If a constant occurs more than once as a predicate argument in ϕ , or if a variable occurs more than once in ϕ , there are multiple τ_i s in $\lceil \phi \rceil$ for that constant or variable. If $\lceil \phi \rceil = \langle \tau_1, \tau_2, \tau_3, \dots, \tau_n \rangle$, the *length* of $\lceil \phi \rceil$ is n . For example, if:

$$\phi = Ntense[t^v, woman(p^v)] \wedge At[1991, Past[e^v, manager_of(p^v, sales)]]$$

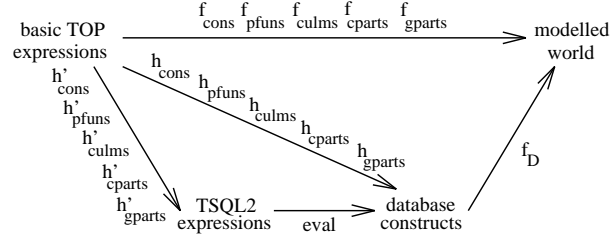


Figure 5.1: Paths from basic TOP expressions to the modelled world

then $\ulcorner \phi \urcorner = \langle t^v, p^v, e^v, p^v, sales \rangle$, and the length of $\ulcorner \phi \urcorner$ is 5.

5.6 Linking the TOP model to the database

As discussed in section 3.6, the answer to an English question submitted at st must report the denotation $\|\phi\|^{M,st}$ of the corresponding TOP formula ϕ . $\|\phi\|^{M,st}$ follows from the semantics of TOP, provided that the model M , which intuitively provides all the necessary information about the modelled world, has been defined. In a NLIDB, the only source of information about the world is the database.¹² Hence, M has to be defined in terms of the information in the database. This mainly involves defining f_{cons} , f_{pfuns} , f_{culms} , f_{cpars} , and f_{gpars} (which are parts of M) in terms of database concepts.

f_{cons} , f_{pfuns} , f_{culms} , f_{cpars} , and f_{gpars} show how certain basic TOP expressions (constants, predicates, and partitioning names) relate to the modelled world. These functions will be defined in terms of the functions h_{cons} , h_{pfuns} , h_{culms} , h_{cpars} , and h_{gpars} (to be discussed in section 5.7), and f_D (section 5.2.1). Roughly speaking, the h functions map basic TOP expressions to database constructs (attribute values or relations), and f_D maps the attribute values of these constructs to world objects (figure 5.1). h_{cons} , h_{pfuns} , h_{culms} , h_{cpars} , and h_{gpars} will in turn be defined in terms of the functions h'_{cons} , h'_{pfuns} , h'_{culms} , h'_{cpars} , and h'_{gpars} (to be discussed in section 5.9), and $eval$ (section 5.4). The h' functions map basic TOP expressions to TSQL2 expressions, and $eval$ maps TSQL2 expressions to database constructs.

After defining the h' functions, one could compute $\|\phi\|^{M,st}$ using a reasoning system, that would contain rules encoding the semantics of TOP, and that would use the path $\text{basic TOP expressions} \rightarrow \text{TSQL2 expressions} \rightarrow \text{database constructs} \rightarrow \text{modelled world}$

¹² This is not entirely true in the framework of this thesis, as there is also a type-hierarchy of world-entities in the HPSG grammar (section 4.2).

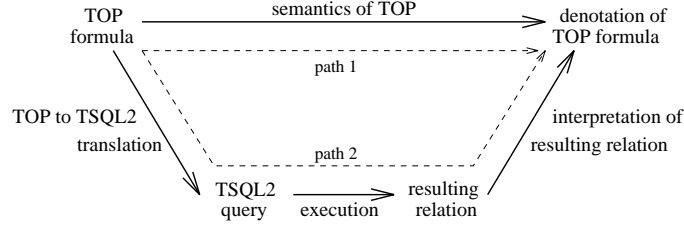


Figure 5.2: Paths from TOP formulae to their denotations

(figure 5.1) to compute any necessary values of f_{cons} , f_{pfuns} , f_{culms} , f_{cparts} , and f_{gparts} . That is, only basic TOP expressions would be translated into TSQL2, and the DBMS would be used only to evaluate the TSQL2 translations of these expressions. The rest of the processing to compute $\|\phi\|^{M,st}$ would be carried out by the reasoning system.

This thesis adopts an alternative approach that exploits the capabilities of the DBMS to a larger extent, and that requires no reasoning system. Based on the h' functions (that map only basic TOP expressions to TSQL2 expressions), a method to translate *any* TOP formula into TSQL2 will be developed. Each TOP formula ϕ will be mapped to a single TSQL2 query (figure 5.2). This will be executed by the DBMS, generating a relation that represents (via an interpretation function) $\|\phi\|^{M,st}$. It will be proven formally that this approach generates indeed $\|\phi\|^{M,st}$ (i.e. that paths 1 and 2 of figure 5.2 lead to the same result).

There is one further complication: the values of f_{cons} , f_{pfuns} , f_{culms} , f_{cparts} , and f_{gparts} will ultimately be obtained by evaluating TSQL2 expressions returned by h'_{cons} , h'_{pfuns} , h'_{culms} , h'_{cparts} , and h'_{gparts} . A TSQL2 expression, however, may generate different results when evaluated at different times (e.g. a SELECT statement may return different results after a database relation on which the statement operates has been updated). This causes the values of f_{cons} , f_{pfuns} , f_{culms} , f_{cparts} , and f_{gparts} to become sensitive to the time where the TSQL2 expressions of the h' functions are evaluated. We want this time to be st , so that the TSQL2 expressions of the h' functions will operate on the information that is in the database when the question is submitted, and so that a TSQL2 literal like PERIOD 'today' (section 5.2.4) in the expressions of the h' functions will be correctly taken to refer to the day that contains st . To accommodate this, f_{cons} , f_{pfuns} , f_{culms} , f_{cparts} , and f_{gparts} must be made sensitive to st :

f_{cons} becomes a function $PTS \mapsto (CONS \mapsto OBJs)$ instead of $CONS \mapsto OBJs$. This

allows the world objects that are assigned to TOP constants via f_{cons} to be different at different sts . Similarly, f_{pfuns} is now a function over PTS . For every $st \in PTS$, $f_{pfuns}(st)$ is in turn a function that maps each pair $\langle \pi, n \rangle$, where $\pi \in PFUNS$ and $n \in \{1, 2, 3, \dots\}$, to another function $(OBS)^n \mapsto pow(PERIODS)$ (cf. the definition of f_{pfuns} in section 3.4). The definitions of f_{culms} , f_{cparts} , and f_{gparts} are modified accordingly. Whatever restrictions applied to f_{cons} , f_{pfuns} , f_{culms} , f_{cparts} , and f_{gparts} , now apply to $f_{cons}(st)$, $f_{pfuns}(st)$, $f_{culms}(st)$, $f_{cparts}(st)$, and $f_{gparts}(st)$, for every $st \in CHRONS$. Also, wherever f_{cons} , f_{pfuns} , f_{culms} , f_{gparts} , f_{cparts} were used in the semantics of TOP, $f_{cons}(st)$, $f_{pfuns}(st)$, $f_{culms}(st)$, and $f_{gparts}(st)$ should now be used. The TOP model also becomes sensitive to st , and is now defined as follows:

$$M(st) = \langle \langle PTS, \prec \rangle, OBS, f_{cons}(st), f_{pfuns}(st), f_{culms}(st), f_{gparts}(st), f_{cparts}(st) \rangle$$

Intuitively, $M(st)$ reflects the history of the world as recorded in the database at st . (If the database supports both valid and transaction time, $M(st)$ reflects the “beliefs” of the database at st ; see section 1.2.4.) The answer to an English question submitted at st must now report the denotation $\|\phi\|^{M(st), st}$ of the corresponding TOP formula ϕ .

5.7 The h functions

I first discuss h_{cons} , h_{pfuns} , h_{culms} , h_{cparts} , and h_{gparts} , the functions that – roughly speaking – map basic TOP expressions to database constructs. As with f_{cons} , f_{pfuns} , f_{culms} , f_{cparts} , and f_{gparts} , the values of h_{cons} , h_{pfuns} , h_{culms} , h_{cparts} , and h_{gparts} will ultimately be obtained by evaluating TSQL2 expressions at st . The results of these evaluations can be different at different sts , and hence the definitions of the h functions must be sensitive to st .

h_{cons} : h_{cons} is a function $PTS \mapsto (CONS \mapsto D)$. For every $st \in PTS$, $h_{cons}(st)$ is in turn a function that maps each TOP constant to an attribute value that represents the same world-entity. For example, $h_{cons}(st)$ could map the TOP constant *sales_department* to the string attribute value *Sales Department*, and the constant *today* to the element of D_P ($D_P \subseteq D$) which denotes the day-period that contains st .

h_{pfuns} : h_{pfuns} is a function over PTS . For every $st \in PTS$, $h_{pfuns}(st)$ is in turn a function over $PFUNS \times \{1, 2, 3, \dots\}$, such that for every $\pi \in PFUNS$ and $n \in \{1, 2, 3, \dots\}$,

$h_{pfuns}(st)(\pi, n) \in NVREL_P(n)$ (section 5.2.3). $h_{pfuns}(st)$ is intended to map every TOP predicate of functor π and arity n to a relation that shows for which arguments of the predicate and at which maximal periods the situation represented by the predicate is true, according to the “beliefs” of the database at st . For example, if $circling(ba737)$ represents the situation where BA737 is circling, and according to the “beliefs” of the database at st , p is a maximal period where BA737 was/is/will be circling, $h_{pfuns}(st)(circling, 1)$ must contain a tuple $\langle v; v_t \rangle$, where $f_D(v) = f_{cons}(ba737)$ (v denotes the flight BA737), and $f_D(v_t) = p$. Similarly, if $h_{pfuns}(st)(circling, 1)$ contains a tuple $\langle v; v_t \rangle$, where $f_D(v) = f_{cons}(ba737)$ and $f_D(v_t) = p$, p is a maximal period where BA737 was/is/will be circling, according to the “beliefs” of the database at st .

h_{culms}: h_{culms} is a function over PTS . For every $st \in PTS$, $h_{culms}(st)$ is in turn a function over $PFUNS \times \{1, 2, 3, \dots\}$, such that for every $\pi \in PFUNS$ and $n \in \{1, 2, 3, \dots\}$, $h_{culms}(st)(\pi, n) \in SREL(n)$. Intuitively, h_{culms} plays the same role as f_{culms} (section 3.4). In practice, h_{culms} is consulted only for predicates that describe situations with inherent climaxes. $h_{culms}(st)$ maps each TOP predicate of functor π and arity n to a relation that shows for which predicate arguments the situation of the predicate reaches its climax at the latest time-point where the situation is ongoing, according to the “beliefs” of the database at st . If, for example, $inspecting(j_adams, ba737)$ represents the situation where J.Adams is inspecting BA737, $h_{pfuns}(st)(inspecting, 2)$ is a relation in $NVREL_P(2)$ and $h_{culms}(st)(inspecting, 2)$ a relation in $SREL(2)$. If, according to the “beliefs” of the database at st , the maximal periods where J.Adams was/is/will be inspecting BA737 are p_1, p_2, \dots, p_j , $h_{pfuns}(st)(inspecting, 2)$ contains the tuples $\langle v_1, v_2; v_t^1 \rangle, \langle v_1, v_2; v_t^2 \rangle, \dots, \langle v_1, v_2; v_t^j \rangle$, where $f_D(v_1) = f_{cons}(j_adams)$, $f_D(v_2) = f_{cons}(ba737)$, and $f_D(v_t^1) = p_1, f_D(v_t^2) = p_2, \dots, f_D(v_t^j) = p_j$. Let us assume that p is the latest maximal period among p_1, \dots, p_j . $h_{culms}(st)(inspecting, 2)$ contains $\langle v_1, v_2 \rangle$ iff according to the “beliefs” of the database at st , the inspection of BA737 by J.Adams reaches its completion at the end of p .

h_{gparts}: h_{gparts} is a function over PTS . For every $st \in PTS$, $h_{gparts}(st)$ is in turn a function that maps every element of $GPARTS$ to an $r \in SREL(1)$, such that the set $S = \{f_D(v) \mid \langle v \rangle \in r\}$ is a gappy partitioning. $h_{gparts}(st)$ is intended to map each TOP gappy partitioning name σ_g to a one-attribute snapshot relation r , whose attribute values represent the periods of the gappy partitioning S that is assigned to σ_g . For

example, $h_{gparts}(st)$ could map $monday^g$ to a one-attribute snapshot relation whose attribute values denote all the Monday-periods.

As with the other h functions, the values of h_{gparts} will ultimately be obtained by evaluating TSQL2 expressions at st (see section 5.9 below). The results of these evaluations can in principle be different at different sts , and this is why h_{gparts} is defined to be sensitive to st . In practice, however, the TSQL2 expressions that are evaluated to obtain the values of h_{gparts} will be insensitive to their evaluation time, and hence the values of h_{gparts} will not depend on st . Similar comments apply to h_{cparts} below.

h_{cparts}: h_{cparts} is a function over PTS . For every $st \in PTS$, $h_{cparts}(st)$ is in turn a function that maps every element of $CPARTS$ to an $r \in SREL(1)$, such that the set $S = \{f_D(v) \mid \langle v \rangle \in r\}$ is a complete partitioning. $h_{cparts}(st)$ is intended to map each TOP complete partitioning name σ_c to a one-attribute snapshot relation r , whose attribute values represent the periods of the complete partitioning S that is assigned to σ_c . For example, $h_{cparts}(st)$ could map day^c to a one-attribute snapshot relation whose attribute values denote all the day-periods.

5.8 The TOP model in terms of database concepts

The TOP model (see section 3.4 and the revisions of section 5.6) can now be defined in terms of database concepts as follows.

Point structure: $\langle PTS, \prec \rangle \stackrel{def}{=} \langle CHRONS, \prec^{chrons} \rangle$

As mentioned in section 5.2.2, $CHRONS \neq \emptyset$, and $\langle CHRONS, \prec^{chrons} \rangle$ has the properties of transitivity, irreflexivity, linearity, left and right boundedness, and discreteness. Hence, $\langle CHRONS, \prec^{chrons} \rangle$ qualifies as a point structure for TOP (section 3.3).

Since $\langle PTS, \prec \rangle = \langle CHRONS, \prec^{chrons} \rangle$, $PERIODS_{\langle PTS, \prec \rangle} = PERIODS_{\langle CHRONS, \prec^{chrons} \rangle}$, and $INSTANTS_{\langle PTS, \prec \rangle} = INSTANTS_{\langle CHRONS, \prec^{chrons} \rangle}$. I write simply $PERIODS$ and $INSTANTS$ to refer to these sets.

OBJS: $OBJS \stackrel{def}{=} OBJS^{db}$

Since $PERIODS \subseteq OBJS^{db}$ (section 5.2.3) and $OBJS = OBJS^{db}$, $PERIODS \subseteq OBJS$, as required by section 3.4.

f_{cons}: For every $st \in PTS$ and $\kappa \in CONS$, I define $f_{cons}(st)(\kappa) \stackrel{def}{=} f_D(h_{cons}(st)(\kappa))$. Since $h_{cons}(st)$ is a function $CONS \mapsto D$, and f_D is a function $D \mapsto OBJS^{db}$, and $OBJ = OBJS^{db}$, $f_{cons}(st)$ is a function $CONS \mapsto OBJS$, as required by section 3.4 and the revisions of section 5.6.

f_{pfuns}: According to section 3.4 and the revisions of section 5.6, for every $st \in PTS$, $f_{pfuns}(st)$ must be a function:

$$PFUNS \times \{1, 2, 3, \dots\} \mapsto ((OBJS)^n \mapsto pow(PERIODS))$$

That is, for every $\pi \in PFUNS$, every $n \in \{1, 2, 3, \dots\}$, and every $o_1, \dots, o_n \in OBJS$, $f_{pfuns}(st)(\pi, n)(o_1, \dots, o_n)$ must be a set of periods. I define $f_{pfuns}(st)(\pi, n)(o_1, \dots, o_n)$ as follows:

$$f_{pfuns}(st)(\pi, n)(o_1, \dots, o_n) \stackrel{def}{=} \{f_D(v_t) \mid \langle f_D^{-1}(o_1), \dots, f_D^{-1}(o_n); v_t \rangle \in h_{pfuns}(st)(\pi, n)\}$$

The restrictions of section 5.7 guarantee that $h_{pfuns}(st)(\pi, n) \in NVREL_P(n)$, which implies that for every $\langle f_D^{-1}(o_1), \dots, f_D^{-1}(o_n); v_t \rangle \in h_{pfuns}(st)(\pi, n)$, $f_D(v_t) \in PERIODS$. Hence, $f_{pfuns}(st)(\pi, n)(o_1, \dots, o_n)$ is a set of periods as wanted.

As discussed in section 5.7, if $\pi(\tau_1, \dots, \tau_n)$ represents some situation, and τ_1, \dots, τ_n denote o_1, \dots, o_n , then $h_{pfuns}(st)(\pi, n)$ contains $\langle f_D^{-1}(o_1), \dots, f_D^{-1}(o_n); v_t \rangle$ iff $f_D(v_t)$ is a maximal period where the situation of $\pi(\tau_1, \dots, \tau_n)$ holds. $f_{pfuns}(st)(\pi, n)(o_1, \dots, o_n)$ is supposed to be the set of the maximal periods where the situation of $\pi(\tau_1, \dots, \tau_n)$ holds. The definition of f_{pfuns} above achieves this.

According to section 3.4 and the revisions of section 5.6, it must also be the case that:

$$\text{if } p_1, p_2 \in f_{pfuns}(st)(\pi, n)(o_1, \dots, o_n) \text{ and } p_1 \cup p_2 \in PERIODS, \text{ then } p_1 = p_2$$

f_{pfuns} , as defined above, has this property. The proof follows. Let us assume that p_1 and p_2 are as above, but $p_1 \neq p_2$. As discussed above, the assumption that $p_1, p_2 \in f_{pfuns}(st)(\pi, n)(o_1, \dots, o_n)$ implies that $p_1, p_2 \in PERIODS$.

Let $v_t^1 = f_D^{-1}(p_1)$ and $v_t^2 = f_D^{-1}(p_2)$ (i.e. $p_1 = f_D(v_t^1)$ and $p_2 = f_D(v_t^2)$). Since, $p_1 \neq p_2$ and f_D^{-1} is 1-1 (section 5.2.1), $f_D^{-1}(p_1) \neq f_D^{-1}(p_2)$, i.e. $v_t^1 \neq v_t^2$. The definition of $f_{pfuns}(st)(\pi, n)(o_1, \dots, o_n)$, the assumptions that $p_1, p_2 \in f_{pfuns}(st)(\pi, n)(o_1, \dots, o_n)$ and that $p_1 \cup p_2 \in PERIODS$, and the fact that $p_1 = f_D(v_t^1)$ and $p_2 = f_D(v_t^2)$ imply that $h_{pfuns}(st)(\pi, n)$ contains the value-equivalent tuples $\langle f_D^{-1}(o_1), \dots, f_D^{-1}(o_n); v_t^1 \rangle$ and

$\langle f_D^{-1}(o_1), \dots, f_D^{-1}(o_n); v_t^2 \rangle$, where $f_D(v_t^1) \cup f_D(v_t^2) \in PERIODS$. This conclusion, the fact that $h_{pfuns}(st)(\pi, n) \in NVREL_P(n)$ (see previous paragraphs), and the definition of $NVREL_P(n)$ (section 5.2.3) imply that $v_t^1 = v_t^2$, which is against the hypothesis. Hence, it cannot be the case that $p_1 \neq p_2$, i.e. $p_1 = p_2$. Q.E.D.

f_{culms}: According to section 3.4 and the revisions of section 5.6, for every $st \in PTS$, $f_{culms}(st)$ must be a function:

$$PFUNS \times \{1, 2, 3, \dots\} \mapsto ((OBS)^n \mapsto \{T, F\})$$

For every $\pi \in PFUNS$, $n \in \{1, 2, 3, \dots\}$, and $o_1, \dots, o_n \in OBS$, I define:

$$f_{culms}(\pi, n)(o_1, \dots, o_n) \stackrel{def}{=} \begin{cases} T, & \text{if } \langle f_D^{-1}(o_1), \dots, f_D^{-1}(o_n) \rangle \in h_{culms}(st)(\pi, n) \\ F, & \text{otherwise} \end{cases}$$

The restrictions of section 5.7, guarantee that $h_{culms}(st)(\pi, n) \in SREL(n)$. As discussed in section 5.7, if a predicate $\pi(\tau_1, \dots, \tau_n)$ represents some situation with an inherent climax, and τ_1, \dots, τ_n denote o_1, \dots, o_n , then $h_{culms}(st)(\pi, n)$ contains $\langle f_D^{-1}(o_1), \dots, f_D^{-1}(o_n) \rangle$ iff the situation reaches its climax at the end of the latest maximal period where the situation is ongoing. $f_{culms}(st)(\pi, n)(o_1, \dots, o_n)$ is supposed to be T iff the situation of $\pi(\tau_1, \dots, \tau_n)$ reaches its climax at the end of the latest maximal period where it is ongoing. The definition of f_{culms} above achieves this.

f_{gparts}: For every $st \in PTS$ and $\sigma_g \in GPARTS$, $f_{gparts}(st)(\sigma_g) \stackrel{def}{=} \{f_D(v) \mid \langle v \rangle \in h_{gparts}(st)(\sigma_g)\}$. The restrictions on h_{gparts} of section 5.7 guarantee that $f_{gparts}(st)(\sigma_g)$ is always a gappy partitioning, as required by section 3.4 and the revisions of section 5.6.

f_{cparts}: For every $st \in PTS$ and $\sigma_c \in CPARTS$, $f_{cparts}(st)(\sigma_c) \stackrel{def}{=} \{f_D(v) \mid \langle v \rangle \in h_{cparts}(st)(\sigma_c)\}$. The restrictions on h_{cparts} of section 5.7 guarantee that $f_{cparts}(st)(\sigma_c)$ is always a complete partitioning, as required by section 3.4 and the revisions of section 5.6.

5.9 The h' functions

I now discuss h'_{cons} , h'_{pfuns} , h'_{culms} , h'_{gparts} , and h'_{cparts} , the functions that map basic TOP expressions (constants, predicates, etc.) to TSQL2 expressions. I assume that

these functions are defined by the configurer of the NLITDB (section 1.2.1).

h'_{cons} : h'_{cons} maps every TOP constant κ to a TSQL2 value expression ξ , such that $FCN(\xi) = \emptyset$, and for every $st \in CHRONS$, $eval(st, \xi) \in D$. (The latter guarantees that $eval(st, \xi) \neq error$.) ξ is intended to represent the same world object as κ . For example, h'_{cons} could map the TOP constant *sales_department* to the TSQL2 value expression 'Sales Department', and the TOP constant *yesterday* to PERIOD 'today' - INTERVAL '1' DAY. In practice, the values of h'_{cons} need to be defined only for TOP constants that are used in the particular application domain. The values of h'_{cons} for other constants are not used, and can be chosen arbitrarily. Similar comments apply to h'_{pfuns} , h'_{culms} , h'_{gparts} , and h'_{cparts} .

h_{cons} is defined in terms of h'_{cons} . For every $st \in CHRONS$ and $\kappa \in CONS$:

$$h_{cons}(st)(\kappa) \stackrel{def}{=} eval(st, h'_{cons}(\kappa))$$

The restrictions above guarantee that $eval(st, h'_{cons}(\kappa)) \in D$. Hence, $h_{cons}(st)$ is a function $CONS \mapsto D$, as required by section 5.7.

h'_{pfuns} : h'_{pfuns} is a function that maps every $\pi \in PFUNS$ and $n \in \{1, 2, 3, \dots\}$ to a TSQL2 SELECT statement Σ , such that $FCN(\Sigma) = \emptyset$, and for every $st \in CHRONS$, $eval(st, \Sigma) \in NVREL_P(n)$. $h'_{pfuns}(\pi, n)$ is intended to be a TSQL2 SELECT statement that generates the relation to which $h_{pfuns}(st)$ maps π and n (the relation that shows for which arguments and at which maximal periods the situation described by $\pi(\tau_1, \dots, \tau_n)$ is true).

h_{pfuns} is defined in terms of h'_{pfuns} . For every $st \in CHRONS$, $\pi \in PFUNS$, and $n \in \{1, 2, 3, \dots\}$:

$$h_{pfuns}(st)(\pi, n) \stackrel{def}{=} eval(st, h'_{pfuns}(\pi, n))$$

The restrictions on h'_{pfuns} above guarantee that $eval(st, h'_{pfuns}(\pi, n)) \in NVREL_P(n)$. Hence, $h_{pfuns}(st)(\pi, n) \in NVREL_P(n)$, as required by section 5.7.

Let us assume, for example, that *manager*(τ) means that τ is a manager, and that *manager_of* is the relation of $NVREL_P(2)$ in (5.42) that shows the maximal periods where somebody is the manager of a department. (To save space, I often omit the names of the explicit attributes. These are not needed, since explicit attributes are referred to by number.)

(5.42)

<i>J.Adams</i>	<i>sales</i>	[1/5/93, 31/12/94]
<i>J.Adams</i>	<i>personnel</i>	[1/1/95, 31/3/95]
<i>J.Adams</i>	<i>research</i>	[5/9/95, 31/12/95]
<i>T.Smith</i>	<i>sales</i>	[1/1/95, 7/5/95]
...

$h'_{pfuns}(manager, 1)$ could be defined to be (5.43), which generates (5.44) ((5.44) is an element of $NVREL_P(1)$, as required by the definition of h'_{pfuns}). The embedded SELECT statement of (5.43) discards the second explicit attribute of *manager_of*. The (PERIOD) coalesces tuples that correspond to the same employees (e.g. the three periods for J.Adams), generating one tuple for each maximal period.

(5.43)

```
SELECT DISTINCT mgr2.1
VALID VALID(mgr2)
FROM (SELECT DISTINCT mgr1.1
      VALID VALID(mgr1)
      FROM manager_of AS mgr1
      )(PERIOD) AS mgr2
```

(5.44)

<i>J.Adams</i>	[1/5/93, 31/3/95]
<i>J.Adams</i>	[5/9/95, 31/12/95]
<i>T.Smith</i>	[1/1/95, 7/5/95]
...	...

h'_{culms} : h'_{culms} is a function that maps every $\pi \in PFUNS$ and $n \in \{1, 2, 3, \dots\}$ to a TSQL2 SELECT statement Σ , such that $FCN(\Sigma) = \emptyset$, and for every $st \in CHRONS$, $eval(st, \Sigma) \in SREL(n)$. $h'_{culms}(\pi, n)$ is intended to be a TSQL2 SELECT statement that generates the relation to which $h_{culms}(st)$ maps π and n (the relation that shows for which arguments of $\pi(\tau_1, \dots, \tau_n)$ the situation of the predicate reaches its climax at the end of the latest maximal period where it is ongoing).

h_{culms} is defined in terms of h'_{culms} . For every $st \in CHRONS$, $\pi \in PFUNS$, and $n \in \{1, 2, 3, \dots\}$:

$$h_{culms}(st)(\pi, n) \stackrel{def}{=} eval(st, h'_{culms}(\pi, n))$$

The restrictions on h'_{culms} above guarantee that $eval(st, h'_{culms}(\pi, n)) \in SREL(n)$. Hence, for every $\pi \in PFUNS$ and $n \in \{1, 2, 3, \dots\}$, $h_{culms}(st)(\pi, n) \in SREL(n)$, as required by section 5.7.

In the airport application, for example, $inspecting(\tau_1, \tau_2, \tau_3)$ means that an occurrence τ_1 of an inspection of τ_3 by τ_2 is ongoing. *inspections* is a relation of the following form:

<i>inspections</i>				
<i>code</i>	<i>inspector</i>	<i>inspected</i>	<i>status</i>	
<i>i158</i>	<i>J.Adams</i>	<i>UK160</i>	<i>complete</i>	[9:00am 1/5/95 – 9:45am 1/5/95] ∪ [10:10am 1/5/95 – 10:25am 1/5/95]
<i>i160</i>	<i>J.Adams</i>	<i>UK160</i>	<i>incomplete</i>	[11:00pm 2/7/95 – 1:00am 3/7/95] ∪ [6:00am 3/7/95 – 6:20am 3/7/95]
<i>i205</i>	<i>T.Smith</i>	<i>BA737</i>	<i>complete</i>	[8:00am 16/11/95 – 8:20am 16/11/95]
<i>i214</i>	<i>T.Smith</i>	<i>BA737</i>	<i>incomplete</i>	[8:10am 14/2/96 – now]

The first tuple above shows that J.Adams started to inspect UK160 at 9:00am on 1/5/95, and continued the inspection up to 9:45am. He resumed the inspection at 10:10am, and completed the inspection at 10:25am on the same day. *status* shows whether or not the inspection reaches its completion at the last time-point of the time-stamp. In the first tuple, its value is *complete*, signaling that the inspection was completed at 10:25am on 1/5/95. The inspection of the second tuple was ongoing from 11:00pm on 2/7/95 to 1:00am on 3/7/95, and from 6:00am to 6:20am on 3/7/95. It did not reach its completion at 6:20am on 3/7/95 (perhaps it was aborted for ever). The inspection of the last tuple started at 8:10am on 14/2/96 and is still ongoing. Each inspection is assigned a unique inspection code, stored as the value of the *code* attribute. The inspection codes are useful to distinguish, for example, J.Adams' inspection of UK160 on 1/5/95 from that on 2-3/7/95 (section 3.16). $h'_{pfun}(inspecting, 3)$ and $h'_{culms}(inspecting, 3)$ are defined to be (5.45) and (5.46) respectively.

(5.45) SELECT DISTINCT insp.1, insp.2, insp.3
 VALID VALID(insp)
 FROM inspections(PERIOD) AS insp

(5.46) SELECT DISTINCT SNAPSHOT inspcmpl.1, inspcmpl.2, inspcmpl.3
 FROM inspections AS inspcmpl
 WHERE inspcmpl.4 = 'complete'

This causes $h_{pfun}(st)(inspecting, 2)$ and $h_{culms}(st)(inspecting, 2)$ to be (5.47) and (5.48) respectively.

(5.47)

<i>i158</i>	<i>J.Adams</i>	<i>UK160</i>	[9:00am 1/5/95, 9:45am 1/5/95]
<i>i158</i>	<i>J.Adams</i>	<i>UK160</i>	[10:10am 1/5/95, 10:25am 1/5/95]
<i>i160</i>	<i>J.Adams</i>	<i>UK160</i>	[11:00pm 2/7/95, 1:00am 3/7/95]
<i>i160</i>	<i>J.Adams</i>	<i>UK160</i>	[6:00am 3/7/95, 6:20am 3/7/95]
<i>i205</i>	<i>T.Smith</i>	<i>BA737</i>	[8:00am 16/11/95, 8:20am 16/11/95]
<i>i214</i>	<i>T.Smith</i>	<i>BA737</i>	[8:10am 14/2/96, now]

(5.48)

<i>i158</i>	<i>J.Adams</i>	<i>UK160</i>
<i>i205</i>	<i>T.Smith</i>	<i>BA737</i>

h'_{gparts} : h'_{gparts} is a function that maps every TOP gappy partitioning name σ_g to a TSQL2 SELECT statement Σ , such that $FCN(\Sigma) = \emptyset$, and for every $st \in CHRONS$, it is true that $eval(st, \Sigma) \in SREL(1)$ and $\{f_D(v) \mid \langle v \rangle \in eval(st, \Sigma)\}$ is a gappy partitioning. $h'_{gparts}(\sigma_g)$ is intended to generate the relation to which $h_{gparts}(st)$ maps σ_g (the relation that represents the members of the gappy partitioning). Assuming, for example, that the *gregorian* calendric relation of section 5.3.3 is available, $h'_{gparts}(sunday^g)$ could be (5.21) of page 210.

h_{gparts} is defined in terms of h'_{gparts} . For every $st \in CHRONS$ and $\sigma_g \in GPARTS$:

$$h_{gparts}(st)(\sigma_g) \stackrel{def}{=} eval(st, h'_{gparts}(\sigma_g))$$

The restrictions on h'_{gparts} and the definition of $h_{gparts}(st)$ above satisfy the requirements on h_{gparts} of section 5.7.

h'_{cparts} : I assume that for each complete partitioning used in the TOP formulae, there is a corresponding TSQL2 granularity (section 5.2.2). h'_{cparts} is a function that maps each TOP complete partitioning name to an ordered pair $\langle \gamma, \Sigma \rangle$, where γ is the name of the corresponding TSQL2 granularity, and Σ is a SELECT statement that returns a relation representing the periods of the partitioning. More precisely, it must be the case that $FCN(\Sigma) = \emptyset$, and for every $st \in CHRONS$, $eval(st, \Sigma) \in SREL(1)$ and $\{f_D(v) \mid \langle v \rangle \in eval(st, \Sigma)\}$ is a complete partitioning. For example, if the *gregorian* relation of section 5.3.3 is available, h'_{cparts} could map day^c to $\langle DAY, \Sigma \rangle$, where Σ is (5.49). (5.49) returns a one-attribute snapshot relation whose attribute values denote all the day-periods.

```
(5.49)  SELECT DISTINCT SNAPSHOT VALID(greg2)
        FROM (SELECT DISTINCT greg1.4
              VALID VALID(greg1)
              FROM gregorian AS greg1
              )(PERIOD) AS greg2
```

h_{cparts} is defined in terms of h'_{cparts} . For every $st \in CHRONS$ and $\sigma_c \in CPARTS$, if $h'_{cparts}(\sigma_c) = \langle \gamma, \Sigma \rangle$, then:

$$h_{cparts}(st)(\sigma_c) = eval(st, \Sigma)$$

The restrictions on h'_{cparts} and the definition of $h_{cparts}(st)$ above satisfy the requirements on h_{cparts} of section 5.7. The γ is used in the translation rule for $For[\sigma_c, \nu_{qty}, \phi]$ (appendix A).

5.10 Formulation of the translation problem

Let us now specify formally what we want the TOP to TSQL2 translation to achieve. I first define *interp* (interpretation of a resulting relation). For every $\phi \in FORMS$ and every relation r :

$$(5.50) \quad interp(r, \phi) \stackrel{def}{=} \begin{cases} T, & \text{if } \phi \in YNFORMS \text{ and } r \neq \emptyset \\ F, & \text{if } \phi \in YNFORMS \text{ and } r = \emptyset \\ \{\langle f_D(v_1), \dots, f_D(v_n) \rangle \mid \langle v_1, \dots, v_n \rangle \in r\}, & \text{if } \phi \in WHFORMS \end{cases}$$

Intuitively, if ϕ was translated to a SELECT statement that generated r , $interp(r, \phi)$ shows how to interpret r . If $\phi \in YNFORMS$ (yes/no English question) and $r \neq \emptyset$, the answer should be affirmative. If $\phi \in YNFORMS$ and $r = \emptyset$, the answer should be negative. Otherwise, if $\phi \in WHFORMS$ (the English question contains interrogatives, e.g. “Who ...?”, “When ...?”), the answer should report all the tuples of world objects $\langle f_D(v_1), \dots, f_D(v_n) \rangle$ represented by tuples $\langle v_1, \dots, v_n \rangle \in r$.

A translation function tr is needed, that maps every $\phi \in FORMS$ to a TSQL2 SELECT statement $tr(\phi)$, such that for every $st \in PTS$, (5.51) and (5.52) hold.

$$(5.51) \quad FCN(tr(\phi)) = \emptyset$$

$$(5.52) \quad interp(eval(st, tr(\phi)), \phi) = \|\phi\|^{M(st), st}$$

$M(st)$ must be as in section 5.6. As discussed in section 3.6, each (reading of an) English question is mapped to a TOP formula ϕ . The answer must report $\|\phi\|^{M(st), st}$. If tr satisfies (5.52), $\|\phi\|^{M(st), st}$ can be computed as $interp(eval(st, tr(\phi)), \phi)$, by letting the DBMS execute $tr(\phi)$ (i.e. compute $eval(st, tr(\phi))$).

tr will be defined in terms of an auxiliary function *trans*. *trans* is a function of two arguments:

$$trans(\phi, \lambda) = \Sigma$$

where $\phi \in FORMS$, λ is a TSQL2 value expression, and Σ a TSQL2 SELECT statement. A set of “translation rules” (to be discussed in section 5.11) specifies the Σ -values of *trans*. In practice, λ always represents a period. Intuitively, λ corresponds to TOP’s *lt*. When *trans* is first invoked (by calling *tr*, discussed below) to translate a formula ϕ , λ is set to PERIOD(TIMESTAMP ‘beginning’, TIMESTAMP ‘forever’) to reflect the fact that TOP’s *lt* is initially set to *PTS* (see the definition of $\|\phi\|^{M, st}$ in section 3.6). *trans*

may call itself recursively to translate subformulae of ϕ (this will become clearer in following sections). When calling *trans* recursively, λ may represent a period that does not cover the whole time-axis, to reflect the fact that already encountered TOP operators may have narrowed *lt*.

I define *tr* as follows:

$$(5.53) \quad tr(\phi) \stackrel{def}{=} trans(\phi, \lambda_{init})$$

where $\lambda_{init} \stackrel{def}{=} \text{PERIOD (TIMESTAMP 'beginning', TIMESTAMP 'forever')}$. Obviously, λ_{init} contains no correlation names, and hence $FCN(\lambda_{init}) = \emptyset$. This implies that $eval(st, \lambda_{init}, g^{db})$ does not depend on g^{db} . λ_{init} evaluates to the element of D_P that represents the period that covers the whole time-axis, i.e. for every $st \in PTS$, it is true that $eval(st, \lambda_{init}) \in D_P$ and $f_D(eval(st, \lambda_{init})) = PTS$. Therefore, lemma 5.1 holds.

Lemma 5.1 $FCN(\lambda_{init}) = \emptyset$, and for every $st \in PTS$, $eval(st, \lambda_{init}) \in D_P$ and $f_D(eval(st, \lambda_{init})) = PTS$.

Using (5.53), (5.51) and (5.52) become (5.54) and (5.55) respectively. The translation rules (that specify the values of *trans* for each ϕ and λ) must be defined so that for every $\phi \in FORMS$ and $st \in PTS$, (5.54) and (5.55) hold.

$$(5.54) \quad FCN(trans(\phi, \lambda_{init})) = \emptyset$$

$$(5.55) \quad interp(eval(st, trans(\phi, \lambda_{init})), \phi) = \|\phi\|^{M(st), st}$$

Appendix A proves that theorems 5.1 and 5.2 hold for the translation rules of this thesis.

Theorem 5.1 If $\phi \in WHFORMS$, $st \in PTS$, $trans(\phi, \lambda_{init}) = \Sigma$, and the total number of interrogative and interrogative-maximal quantifiers in ϕ is n , then:

1. $FCN(\Sigma) = \emptyset$
2. $eval(st, \Sigma) \in SREL(n)$
3. $\{\langle f_D(v_1), \dots, f_D(v_n) \rangle \mid \langle v_1, \dots, v_n \rangle \in eval(st, \Sigma)\} = \|\phi\|^{M(st), st}$

That is, the translation Σ of ϕ contains no free column references, and it evaluates to a snapshot relation of n attributes, whose tuples represent $\|\phi\|^{M(st), st}$.

Theorem 5.2 If $\phi \in \text{YNFORMS}$, $st \in \text{PTS}$, λ is a TSQL2 expression, $g^{db} \in G^{db}$, $eval(st, \lambda, g^{db}) \in D_P^*$, $\ulcorner \phi \urcorner = \langle \tau_1, \dots, \tau_n \rangle$, and $\Sigma = trans(\phi, \lambda)$, then:

1. $FCN(\Sigma) \subseteq FCN(\lambda)$
2. $eval(st, \Sigma, g^{db}) \in VREL_P(n)$
3. $\langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$ iff for some $g \in G$:
 $\|\tau_1\|^{M(st),g} = f_D(v_1), \dots, \|\tau_n\|^{M(st),g} = f_D(v_n)$, and
 $\|\phi\|^{M(st),st,f_D(v_t),f_D(eval(st,\lambda,g^{db})),g} = T$

$\tau_1, \tau_2, \dots, \tau_n$ are all the constants in predicate argument positions and all the variables in ϕ (section 5.5). Clause 3 intuitively means that the tuples of $eval(st, \Sigma, g^{db})$ represent all the possible combinations of values of τ_1, \dots, τ_n and event times et , such that $\|\phi\|^{M(st),st,et,lt,g} = T$, where lt is the element of $PERIODS^*$ represented by λ .

I now prove that theorems 5.1 and 5.2 imply that (5.54) and (5.55) hold for every $st \in \text{PTS}$ and $\phi \in \text{FORMS}$, i.e. that $trans$ has the desired properties.

Proof of (5.54): Let $st \in \text{PTS}$ and $\phi \in \text{FORMS}$. We need to show that (5.54) holds. Since $\text{FORMS} = \text{WHFORMS} \cup \text{YNFORMS}$, the hypothesis that $\phi \in \text{FORMS}$ implies that $\phi \in \text{WHFORMS}$ or $\phi \in \text{YNFORMS}$. In both cases (5.54) holds:

- If $\phi \in \text{WHFORMS}$, then by theorem 5.1, $FCN(trans(\phi, \lambda_{init})) = \emptyset$, i.e. (5.54) holds.
- If $\phi \in \text{YNFORMS}$, then by theorem 5.2 and lemma 5.1, the following holds, which implies that (5.54) also holds.

$$FCN(trans(\phi, \lambda_{init})) \subseteq FCN(\lambda_{init}) = \emptyset$$

Proof of (5.55): Let $st \in \text{PTS}$ and $\phi \in \text{FORMS}$. Again, it will either be the case that $\phi \in \text{WHFORMS}$ or $\phi \in \text{YNFORMS}$.

If $\phi \in \text{WHFORMS}$, then by theorem 5.1 the following is true:

$$\{\langle f_D(v_1), \dots, f_D(v_n) \rangle \mid \langle v_1, \dots, v_n \rangle \in eval(st, trans(\phi, \lambda_{init}))\} = \|\phi\|^{M(st),st}$$

The definition of *interp*, the hypothesis that $\phi \in \text{WHFORMS}$, and the equation above imply (5.55).

It remains to prove (5.55) for $\phi \in \text{YNFORMS}$. Let $\ulcorner \phi \urcorner = \langle \tau_1, \dots, \tau_n \rangle$. By lemma 5.1, for every $g^{db} \in G^{db}$, $\text{eval}(st, \lambda_{init}, g^{db}) = \text{eval}(st, \lambda_{init}) \in D_P$ and $f_D(\text{eval}(st, \lambda_{init})) = PTS$. Also, (5.54) (proven above) implies that $\text{eval}(st, \text{trans}(\phi, \lambda_{init}), g^{db})$ does not depend on g^{db} . Then, from theorem 5.2 we get (5.56) and (5.57).

$$(5.56) \quad \text{eval}(st, \text{trans}(\phi, \lambda_{init})) \in VREL_P(n)$$

$$(5.57) \quad \langle v_1, \dots, v_n; v_t \rangle \in \text{eval}(st, \text{trans}(\phi, \lambda_{init})) \text{ iff for some } g \in G: \\ \|\tau_1\|^{M(st),g} = f_D(v_1), \dots, \|\tau_n\|^{M(st),g} = f_D(v_n), \text{ and} \\ \|\phi\|^{M(st),st,f_D(v_t),PTS,g} = T$$

The hypothesis that $\phi \in \text{YNFORMS}$ and the definition of *interp* imply that the left-hand side of (5.55) has the following values:

$$\begin{cases} T, & \text{if } \text{eval}(st, \text{trans}(\phi, \lambda_{init})) \neq \emptyset \\ F, & \text{if } \text{eval}(st, \text{trans}(\phi, \lambda_{init})) = \emptyset \end{cases}$$

The hypothesis that $\phi \in \text{YNFORMS}$ and the definition of $\|\phi\|^{M(st),st}$ (section 3.6) imply that the right-hand side of (5.55) has the following values:

$$\begin{cases} T, & \text{if for some } g \in G \text{ and } et \in PERIODS, \|\phi\|^{M(st),st,et,PTS,g} = T \\ F, & \text{otherwise} \end{cases}$$

Hence, to prove (5.55) it is enough to prove (5.58).

$$(5.58) \quad \text{eval}(st, \text{trans}(\phi, \lambda_{init})) \neq \emptyset \text{ iff} \\ \text{for some } g \in G \text{ and } et \in PERIODS, \|\phi\|^{M(st),st,et,PTS,g} = T$$

I first prove the forward direction of (5.58). If it is true that $\text{eval}(st, \text{trans}(\phi, \lambda_{init})) \neq \emptyset$, by (5.56) $\text{eval}(st, \text{trans}(\phi, \lambda_{init}))$ contains at least a tuple of the form $\langle v_1, \dots, v_n; v_t \rangle$, i.e. (5.59) is true.

$$(5.59) \quad \langle v_1, \dots, v_n; v_t \rangle \in \text{eval}(st, \text{trans}(\phi, \lambda_{init}))$$

(5.59) and (5.57) imply that for some $g \in G$, (5.60) holds.

$$(5.60) \quad \|\phi\|^{M(st),st,f_D(v_t),PTS,g} = T$$

(5.56) and (5.59) imply that v_t is the time-stamp of a tuple in a relation of $VREL_P$, which implies that $f_D(v_t) \in PERIODS$. Let $et = f_D(v_t)$. Then, (5.60) becomes (5.61),

where $g \in G$ and $et = f_D(v_t) \in PERIODS$. The forward direction of (5.58) has been proven.

$$(5.61) \quad \|\phi\|^{M(st),st,et,PTS,g} = T$$

I now prove the backwards direction of (5.58). I assume that $g \in G$, $et \in PERIODS$, and $\|\phi\|^{M(st),st,et,PTS,g} = T$. Let $v_t = f_D^{-1}(et)$, which implies that $et = f_D(v_t)$. Then (5.62) holds.

$$(5.62) \quad \|\phi\|^{M(st),st,f_D(v_t),PTS,g} = T$$

Let $v_1 = f_D^{-1}(\|\tau_1\|^{M(st),g})$, \dots , $v_n = f_D^{-1}(\|\tau_n\|^{M(st),g})$. This implies that (5.63) also holds.

$$(5.63) \quad \|\tau_1\|^{M(st),g} = f_D(v_1), \dots, \|\tau_n\|^{M(st),g} = f_D(v_n)$$

(5.63), (5.62), the hypothesis that $g \in G$, and (5.57) imply (5.64), which in turn implies that $eval(st, trans(\phi, \lambda_{init})) \neq \emptyset$. The backwards direction of (5.58) has been proven.

$$(5.64) \quad \langle v_1, \dots, v_n; v_t \rangle \in eval(st, trans(\phi, \lambda_{init}))$$

This concludes the proof of (5.55). I have proven that *trans* satisfies (5.54) and (5.55) for every $\phi \in FORMS$ and $st \in PTS$, i.e. that *trans* has all the desired properties.

5.11 The translation rules

The values (SELECT statements) of *trans* are specified by a set of “translation rules”. These rules are of two kinds: (a) base (non-recursive) rules that specify $trans(\phi, \lambda)$ when ϕ is an atomic formula or a formula of the form $Culm[\pi(\tau_1, \dots, \tau_n)]$; and (b) recursive rules that specify $trans(\phi, \lambda)$ in all other cases, by recursively calling other translation rules to translate subformulae of ϕ . In this section, I attempt to convey the intuitions behind the design of the translation rules, and to illustrate the functionality of some representative rules.

In the case of a yes/no formula ϕ , the aim is for the resulting SELECT statement to return a relation of $VREL_P(n)$ that shows all the combinations of event-times et and values of τ_1, \dots, τ_n ($\langle \tau_1, \dots, \tau_n \rangle = \ulcorner \phi \urcorner$) for which ϕ is satisfied. More precisely, the tuples of the relation must represent all the combinations of event times et and world

objects assigned (by $f_{cons}(st)$ and some variable assignment g) to τ_1, \dots, τ_n , for which $\|\phi\|^{M(st),st,et,lt,g} = T$, where lt is the element of $PERIODS^*$ represented by λ . In each tuple $\langle v_1, \dots, v_n; v_t \rangle$, v_t represents et , while v_1, \dots, v_n represent the world objects of τ_1, \dots, τ_n . For example, the rule for predicates is as follows:

Translation rule for predicates:

$trans(\pi(\tau_1, \dots, \tau_n), \lambda) \stackrel{def}{=} \\$
 (SELECT DISTINCT $\alpha.1, \alpha.2, \dots, \alpha.n$
 VALID VALID(α)
 FROM ($h'_{pfuns}(\pi, n)$)(SUBPERIOD) AS α
 WHERE ...
 AND ...
 ...
 AND ...
 AND λ CONTAINS VALID(α))

where the “...”s in the WHERE clause stand for all the strings in $S_1 \cup S_2$, and:

$$S_1 = \{“\alpha.i = h'_{cons}(\tau_i)” \mid i \in \{1, 2, 3, \dots, n\} \text{ and } \tau_i \in CONS\}$$

$$S_2 = \{“\alpha.i = \alpha.j” \mid i, j \in \{1, 2, 3, \dots, n\}, i < j, \tau_i = \tau_j, \text{ and } \tau_i, \tau_j \in VARS\}$$

I assume that whenever the translation rule is invoked, a new correlation name α is used, that is obtained by calling a *generator of correlation names*. Whenever called, the generator returns a new correlation name that has never been generated before. I assume that the correlation names of the generator are of some distinctive form (e.g. $t1, t2, t3, \dots$), and that the correlation names in the SELECT statements returned by h'_{pfuns} , h'_{culms} , h'_{cparts} , and h'_{gparts} are not of this distinctive form. I also assume that some mechanism is in place to ensure that no correlation name of the distinctive form of the generator can be used before it has been generated. The use of the generator means that *trans* is strictly speaking not a pure function, since the same π and τ_1, \dots, τ_n lead to slightly different SELECT statements whenever $trans(\pi(\tau_1, \dots, \tau_n), \lambda)$ is computed: each time the resulting statement contains a different α (similar comments apply to other translation rules). There are ways to make *trans* a pure function, but these complicate the translation rules and the proof of their correctness, without offering any practical advantage.

Let us consider, for example, the predicate *inspecting*(*i158*, *j_adams*, *uk160*). According to section 3.6, $\|inspecting(i158, j_adams, uk160)\|^{M(st),st,et,lt,g} = T$ iff $et \sqsubseteq lt$ and

$et \sqsubseteq p$, where:

$$p \in f_{pfuns}(st)(inspecting, 3)(\|i158\|^{M(st),g}, \|j_adams\|^{M(st),g}, \|uk160\|^{M(st),g})$$

Let us assume that $h'_{pfuns}(inspecting, 3)$ and $h_{pfuns}(st)(inspecting, 3)$ are (5.45) and (5.47) respectively (p. 228), that *i158*, *j_adams*, and *uk160* correspond to the obvious attribute values of (5.47), and that λ is PERIOD '[9:00am 1/5/95 - 9:30pm 1/5/95]'. *lt* is the period represented by λ . By the definition of f_{pfuns} of section 5.8:

$$f_{pfuns}(st)(inspecting, 3)(\|i158\|^{M(st),g}, \|j_adams\|^{M(st),g}, \|uk160\|^{M(st),g}) = \{p_1, p_2\}$$

where p_1 and p_2 are the periods of the first two tuples of (5.47). The denotation of $inspecting(i158, j_adams, uk160)$ is T for all the *ets* that are subperiods of p_1 or p_2 and also subperiods of *lt*.

The translation rule above maps $inspecting(i158, j_adams, uk160)$ to (5.65), where $h'_{pfuns}(inspecting, 3)$ is the SELECT statement of (5.45) (that returns (5.47)).

(5.65)

```
(SELECT DISTINCT t1.1, t1.2, t1.3
  VALID VALID(t1)
FROM (h'_{pfuns}(inspecting, 3))(SUBPERIOD) AS t1
WHERE t1.1 = 'i158'
      AND t1.2 = 'J.Adams'
      AND t1.3 = 'UK160'
      AND PERIOD '[9:00am 1/5/95 - 9:30pm 1/5/95]' CONTAINS VALID(t1))
```

(5.65) returns (5.66), where the time-stamps correspond to all the subperiods of p_1 and p_2 (p_1 and p_2 are the periods of the first two time-stamps of (5.47)) that are also subperiods of *lt* (the period represented by λ).

(5.66)

<i>i158</i>	<i>J.Adams</i>	<i>UK160</i>	[9:00am 1/5/95, 9:30pm 1/5/95]
<i>i158</i>	<i>J.Adams</i>	<i>UK160</i>	[9:10am 1/5/95, 9:15pm 1/5/95]
<i>i158</i>	<i>J.Adams</i>	<i>UK160</i>	[9:20am 1/5/95, 9:25pm 1/5/95]
...

In other words, the time-stamps of (5.66) represent correctly all the *ets* where the denotation of $inspecting(i158, j_adams, uk160)$ is T . In this example, all the predicate arguments are constants. Hence, there can be no variation in the values of the arguments, and the values of the explicit attributes in (5.66) are the same in all the tuples. When some of the predicate arguments are variables, the values of the corresponding explicit attributes are not necessarily fixed.

The S_2 constraints in the **WHERE** clause of the translation rule are needed when the predicate contains the same variable in more than one argument positions. In those cases, S_2 requires the attributes that correspond to the argument positions where the variable appears to have the same values. S_2 contains redundant constraints when some variable appears in more than two argument positions. For example, in $\pi(\beta, \beta, \beta)$ ($\beta \in \text{VARS}$), S_2 requires the tuples $\langle v_1, v_2, v_3; v_t \rangle$ of the resulting relation to satisfy: $v_1 = v_2$, $v_1 = v_3$, and $v_2 = v_3$. The third constraint is redundant, because it follows from the others. The prototype NLITDB employs a slightly more complex definition of S_2 that does not generate the third constraint. Similar comments apply to the rule for $\text{Culm}[\pi(\tau_1, \dots, \tau_n)]$ below, and the rules for conjunction, $\text{At}[\phi_1, \phi_2]$, $\text{Before}[\phi_1, \phi_2]$, and $\text{After}[\phi_1, \phi_2]$ (appendix A).

Translation rule for $\text{Culm}[\pi(\tau_1, \dots, \tau_n)]$:

$\text{trans}(\text{Culm}[\pi(\tau_1, \dots, \tau_n)], \lambda) \stackrel{\text{def}}{=} \\ \begin{aligned} &(\text{SELECT DISTINCT } \alpha_1.1, \alpha_1.2, \dots, \alpha_1.n \\ &\quad \text{VALID PERIOD}(\text{BEGIN}(\text{VALID}(\alpha_1)), \text{END}(\text{VALID}(\alpha_1))) \\ &\text{FROM } (h'_{pfun}(\pi, n))(\text{ELEMENT}) \text{ AS } \alpha_1, \\ &\quad (h'_{culms}(\pi, n)) \text{ AS } \alpha_2 \\ &\text{WHERE } \alpha_1.1 = \alpha_2.1 \\ &\quad \text{AND } \alpha_1.2 = \alpha_2.2 \\ &\quad \vdots \\ &\quad \text{AND } \alpha_1.n = \alpha_2.n \\ &\quad \text{AND } \dots \\ &\quad \vdots \\ &\quad \text{AND } \dots \\ &\quad \text{AND } \lambda \text{ CONTAINS PERIOD}(\text{BEGIN}(\text{VALID}(\alpha_1)), \text{END}(\text{VALID}(\alpha_1))) \end{aligned}$

Whenever the rule is used, α_1 and α_2 are two new different correlation names, obtained by calling the correlation names generator after λ has been supplied. The “ \dots ” in the **WHERE** clause stand for all the strings in $S_1 \cup S_2$, where S_1 and S_2 are as in the translation rule for predicates, except that α is now α_1 .

The rule for $\text{Culm}[\pi(\tau_1, \dots, \tau_n)]$ is similar to that for $\pi(\tau_1, \dots, \tau_n)$. The resulting **SELECT** statement returns an element of $\text{VREL}_P(n)$ that shows the *ets* and the values of the predicate arguments for which the denotation of $\text{Culm}[\pi(\tau_1, \dots, \tau_n)]$ is T . In the case of $\text{Culm}[\pi(\tau_1, \dots, \tau_n)]$, however, the generated relation contains only tuples $\langle v_1, \dots, v_n; v_t \rangle$, for which $\langle v_1, \dots, v_n \rangle$ appears in $h_{culms}(st)(\pi, n)$ (the relation returned by $h'_{culms}(\pi, n)$). That is, the situation of $\pi(\tau_1, \dots, \tau_n)$ must reach its climax at the latest time-point where it is ongoing. Also, $h_{pfun}(st)(\pi, n)$ (the relation returned by $h'_{pfun}(\pi, n)$) is coalesced using (**ELEMENT**). This causes all tuples of

$h_{pfuns}(st)(\pi, n)$ that refer to the same situation to be merged into one tuple, time-stamped by a temporal element that is the union of all the periods where the situation is ongoing. Let us refer to this coalesced version of $h_{pfuns}(st)(\pi, n)$ as r . α_1 ranges over the tuples of r , while α_2 over the tuples of $h_{culms}(st)(\pi, n)$. The relation returned by $trans(Culm[\pi(\tau_1, \dots, \tau_n)], \lambda)$ contains all tuples $\langle v_1, \dots, v_n; v_t \rangle$, such that $\langle v_1, \dots, v_n; v'_t \rangle \in r$, v_t represents the period that starts at the beginning of the temporal element of v'_t and ends at the end of the temporal element of v'_t , $\langle v_1, \dots, v_n \rangle \in h_{culms}(st)(\pi, n)$, and v_t 's period (i.e. et) is a subperiod of λ 's period (i.e. lt). S_1 and S_2 play the same role as in the translation rule for predicates.

Let us assume that $h'_{pfuns}(inspecting, 3)$ and $h'_{culms}(inspecting, 3)$ are (5.45) and (5.46) respectively, that $h_{pfuns}(st)(inspecting, 3)$ and $h_{culms}(st)(inspecting, 3)$ are (5.47) and (5.48), and that $\lambda = \text{PERIOD } '[1/5/95 - 18/11/95]'$. The translation rule above maps $Culm[inspecting(occr^v, person^v, flight^v)]$ to (5.67).

(5.67)

```
(SELECT DISTINCT t1.1, t1.2, t1.3
  VALID PERIOD(BEGIN(VALID(t1)), END(VALID(t1)))
FROM (h'_{pfuns}(inspecting, 3))(ELEMENT) AS t1,
      (h'_{culms}(inspecting, 3)) AS t2
WHERE t1.1 = t2.1
      AND t1.2 = t2.2
      AND t1.3 = t2.3
      AND PERIOD '[1/5/95 - 18/11/95]' CONTAINS
      PERIOD(BEGIN(VALID(t1)), END(VALID(t1))))
```

(5.67) returns (5.68). There is (correctly) no tuple for inspection *i160*: the semantics of *Culm* (section 3.9) requires the inspection to reach its completion at the latest time-point where it is ongoing; according to (5.48), this is not the case for *i160*. There is also (correctly) no tuple for *i214*: the semantics of *Culm* requires et (the time of the inspection) to be a subperiod of lt (λ 's period), but *i214* does not occur within lt . Finally, (5.68) does not contain tuples for the subperiods of [9:00am 1/5/95, 10:25am 1/5/95] and [8:00am 16/11/95, 8:20am 16/11/95]. This is in accordance with the semantics of *Culm*, that allows $Culm[inspecting(occr^v, j_adams, ba737)]$ to be true only at ets that cover entire inspections (from start to completion).

(5.68)

<i>i158</i>	<i>J.Adams</i>	<i>UK160</i>	[9:00am 1/5/95, 10:25am 1/5/95]
<i>i205</i>	<i>T.Smith</i>	<i>BA737</i>	[8:00am 16/11/95, 8:20am 16/11/95]

All the other translation rules for yes/no formulae are recursive. For example, $Past[\beta, \phi']$ is translated using the following:

Translation rule for $Past[\beta, \phi']$:

$trans(Past[\beta, \phi'], \lambda) \stackrel{def}{=} \\ (SELECT\ DISTINCT\ VALID(\alpha),\ \alpha.1,\ \alpha.2,\ \dots,\ \alpha.n \\ VALID\ VALID(\alpha) \\ FROM\ trans(\phi', \lambda')\ AS\ \alpha)$

λ' is the expression $INTERSECT(\lambda, PERIOD(TIMESTAMP\ 'beginning', TIMESTAMP\ 'now' - INTERVAL\ '1'\ \chi))$, χ stands for the TSQL2 name of the granularity of chronons (e.g. DAY), and n is the length of $\lceil \phi' \rceil$. Whenever the rule is used, α is a new correlation name obtained by calling the correlation names generator.

The rule for $Past[\beta, \phi']$ calls recursively $trans$ to translate ϕ' . ϕ' is translated with respect to λ' , which represents the intersection of the period of the original λ with the period that covers all the time up to (but not including) the present chronon. This reflects the semantics of $Past$ (section 3.8), that narrows lt to $lt \cap [t_{first}, st)$. The relation returned by $trans(Past[\beta, \phi'], \lambda)$ is the same as that of $trans(\phi', \lambda')$, except that the relation of $trans(Past[\beta, \phi'], \lambda)$ contains an additional explicit attribute, that corresponds to the β of $Past[\beta, \phi']$. The values of that attribute are the same as the corresponding time-stamps (that represent et). This reflects the semantics of $Past[\beta, \phi']$, that requires the value of β to be et . As a further example, $At[\kappa, \phi']$ ($\kappa \in CONS$) is translated using the following:

Translation rule for $At[\kappa, \phi']$:

$trans(At[\kappa, \phi'], \lambda) \stackrel{def}{=} trans(\phi', \lambda')$, where λ' is $INTERSECT(\lambda, h'_{cons}(\kappa))$.

The translation of $At[\kappa, \phi']$ is the same as the translation of ϕ' , but ϕ' is translated with respect to λ' , which represents the intersection of λ 's period with that of κ . This reflects the fact that in $At[\kappa, \phi']$, the At narrows lt to the intersection of the original lt with κ 's period. There are separate translation rules for $At[\sigma_c, \beta, \phi']$, $At[\sigma_g, \beta, \phi']$, and $At[\phi_1, \phi_2]$ ($\sigma_c \in CPARTS$, $\sigma_g \in GPARTS$, and $\phi', \phi_1, \phi_2 \in YNFORMS$).

The complete set of translation rules for yes/no formulae is given in appendix A, along with a formal proof that $trans(\phi, \lambda)$ satisfies theorem 5.2. Theorem 5.2 is proven by induction on the syntactic complexity of ϕ . I first prove that theorem 5.2 holds if ϕ is a predicate or $Culm[\pi(\tau_1, \dots, \tau_n)]$. For all other $\phi \in YNFORMS$, ϕ is non-atomic. In those cases, I prove that theorem 5.2 holds if it holds for the subformulae of ϕ .

Let us now consider wh-formulae. These have the form $? \beta_1\ ? \beta_2\ ? \beta_3 \dots ? \beta_k\ \phi'$ or $?_{maxl} \beta_1\ ? \beta_2\ ? \beta_3 \dots ? \beta_k\ \phi'$, where $\phi' \in YNFORMS$ (section 3.2). The first case is

covered by the following rule. (The rules for wh-formulae define $trans(\phi, \lambda)$ only for $\lambda = \lambda_{init}$. The values of $trans$ for $\phi \in WHFORMS$ and $\lambda \neq \lambda_{init}$ are not used anywhere and can be chosen arbitrarily. Intuitively, for $\phi \in WHFORMS$ the goal is to define $trans(\phi, \lambda)$ so that it satisfies theorem 5.1. That theorem is indifferent to the values of $trans$ for $\lambda \neq \lambda_{init}$.)

Translation rule for $? \beta_1 ? \beta_2 ? \beta_3 \dots ? \beta_k \phi'$:

$$trans(? \beta_1 ? \beta_2 ? \beta_3 \dots ? \beta_k \phi', \lambda_{init}) \stackrel{def}{=}$$

```
(SELECT DISTINCT SNAPSHOT  $\alpha.\omega_1, \alpha.\omega_2, \dots, \alpha.\omega_k$ 
FROM  $trans(\phi', \lambda_{init})$  AS  $\alpha$ )
```

Whenever the rule is used, α is a new correlation name, obtained by calling the correlation names generator. Assuming that $\lceil \phi' \rceil = \langle \tau_1, \dots, \tau_n \rangle$, for every $i \in \{1, 2, 3, \dots, \kappa\}$:

$$\omega_i = \min(\{j \mid j \in \{1, 2, 3, \dots, n\} \text{ and } \tau_j = \beta_i\})$$

That is, the first position (from left to right) where β_i appears in $\langle \tau_1, \dots, \tau_n \rangle$ is the ω_i -th one. Intuitively, we want $? \beta_1 ? \beta_2 ? \beta_3 \dots ? \beta_k \phi'$ to be translated to a **SELECT** statement that returns a snapshot relation, whose tuples represent $\|? \beta_1 ? \beta_2 ? \beta_3 \dots ? \beta_k \phi'\|^{M(st), st}$. According to section 3.6, $\|? \beta_1 ? \beta_2 ? \beta_3 \dots ? \beta_k \phi'\|^{M(st), st}$ is the set of all tuples that represent combinations of values assigned to β_1, \dots, β_k by some $g \in G$, such that for some $et \in PERIODS$, $\|\phi'\|^{M(st), st, et, PTS, g} = T$.

By theorem 5.2, the relation returned by $trans(\phi', \lambda_{init})$ (see the translation rule) is a valid-time relation, whose tuples show all the possible combinations of *ets* and values assigned (by $f_{cons}(st)$ and some $g \in G$) to τ_1, \dots, τ_n , for which $\|\phi'\|^{M(st), st, et, PTS, g} = T$. The syntax of TOP (section 3.2) guarantees that β_1, \dots, β_k appear within ϕ' . This in turn guarantees that β_1, \dots, β_k appear among τ_1, \dots, τ_n , i.e. the relation of $trans(\phi', \lambda_{init})$ contains attributes for β_1, \dots, β_k . To find all the possible combinations of values of β_1, \dots, β_k for which (for some et) $\|\phi'\|^{M(st), st, et, PTS, g} = T$, we simply need to pick (to “project” in relational terms) from the relation of $trans(\phi', \lambda_{init})$ the attributes that correspond to β_1, \dots, β_k . For $i \in \{1, 2, 3, \dots, k\}$, β_i may appear more than once in ϕ' . In this case, the relation of $trans(\phi', \lambda_{init})$ contains more than one attributes for β_i (these attributes have the same values in each tuple). We only need to project one of the attributes that correspond to β_i . The translation rule projects only the first one; this is the ω_i -th attribute of $trans(\phi', \lambda_{init})$, the attribute that corresponds to the first (from left to right) τ_j in $\langle \tau_1, \dots, \tau_n \rangle$ that is equal to β_i .

Let us consider, for example, the following wh-formula (“Who inspected what?”):

$$(5.69) \quad ?w1^v ?w2^v \text{ Past}[e^v, \text{Culm}[\text{inspecting}(\text{occr}^v, w1^v, w2^v)]]$$

Here, $\phi' = \text{Past}[e^v, \text{Culm}[\text{inspecting}(\text{occr}^v, w1^v, w2^v)]]$ and $\lceil \phi' \rceil = \langle e^v, \text{occr}^v, w1^v, w2^v \rangle$. Let us assume that $\text{trans}(\phi', \lambda_{\text{init}})$ returns (5.70). (5.70) shows all the possible combinations of *ets* and values that can be assigned by some $g \in G$ to e^v , occr^v , $w1^v$, and $w2^v$, such that $\|\phi'\|^{M(st), st, et, PTS, g} = T$. In every tuple, the time-stamp is the same as the value of the first explicit attribute, because the semantics of *Past* requires the value of e^v (represented by the first explicit attribute) to be *et* (represented by the time-stamp). To save space, I omit the time-stamps of (5.70).

$$(5.70) \quad \begin{array}{|l|l|l|l|l|} \hline [9:00am\ 1/5/95, 3:00pm\ 1/5/95] & i158 & J.Adams & UK160 & \dots \\ \hline [10:00am\ 4/5/95, 11:30am\ 4/5/95] & i165 & J.Adams & BA737 & \dots \\ \hline [7:00am\ 16/11/95, 7:30am\ 16/11/95] & i204 & T.Smith & UK160 & \dots \\ \hline \end{array}$$

To generate the snapshot relation that represents $\|\text{?}w1^v \text{?}w2^v \phi'\|^{M(st), st}$, i.e. the relation that shows the combinations of values of $w1^v$ and $w2^v$ for which (for some *et* and *g*) $\|\text{Past}[e^v, \text{Culm}[\text{inspecting}(\text{occr}^v, w1^v, w2^v)]]\|^{M(st), st, et, PTS, g} = T$, we simply need to project the explicit attributes of (5.70) that correspond to $w1^v$ and $w2^v$. The first positions where $w1^v$ and $w2^v$ appear in $\lceil \phi' \rceil = \langle e^v, \text{occr}^v, w1^v, w2^v \rangle$ are the third and fourth (i.e. $\omega_1 = 3$ and $\omega_2 = 4$). Hence, we need to project the third and fourth explicit attributes of (5.70). The translation rule for $\text{?}\beta_1 \dots \text{?}\beta_k \phi'$ maps (5.69) to (5.71), which achieves exactly that (it returns (5.72)).

$$(5.71) \quad \begin{array}{l} \text{(SELECT DISTINCT SNAPSHOT t1.3, t1.4} \\ \text{FROM trans(Past}[e^v, \text{Culm}[\text{inspecting}(\text{occr}^v, w1^v, w2^v)]]], \lambda_{\text{init}}) \text{ AS t1)} \end{array}$$

$$(5.72) \quad \begin{array}{|l|l|} \hline J.Adams & UK160 \\ \hline J.Adams & BA737 \\ \hline T.Smith & UK160 \\ \hline \end{array}$$

Wh-formulae of the form $\text{?}_{mxl}\beta_1 \text{?}\beta_2 \text{?}\beta_3 \dots \text{?}\beta_k \phi'$ ($\phi' \in \text{YNFORMS}$) are translated using the following:

Translation rule for $\text{?}_{mxl}\beta_1 \text{?}\beta_2 \text{?}\beta_3 \dots \text{?}\beta_k \phi'$:

$$\text{trans}(\text{?}_{mxl}\beta_1 \text{?}\beta_2 \text{?}\beta_3 \dots \text{?}\beta_k \phi', \lambda_{\text{init}}) \stackrel{\text{def}}{=} \text{trans}(\text{?}_{mxl}\beta_1 \text{?}\beta_2 \text{?}\beta_3 \dots \text{?}\beta_k \phi', \lambda_{\text{init}})$$

$$\begin{array}{l} \text{(SELECT DISTINCT SNAPSHOT VALID}(\alpha_2), \alpha_2.2, \alpha_2.3, \dots, \alpha_2.k \\ \text{FROM (SELECT DISTINCT 'dummy', } \alpha_1.\omega_2, \alpha_1.\omega_3, \dots, \alpha_1.\omega_k \\ \text{VALID } \alpha_1.\omega_1 \\ \text{FROM trans}(\phi', \lambda_{\text{init}}) \text{ AS } \alpha_1 \\ \text{) (NOSUBPERIOD) AS } \alpha_2) \end{array}$$

Whenever the rule is used, α_1 and α_2 are two different new correlation names, obtained by calling the correlation names generator. Assuming that $\lceil \phi' \rceil = \langle \tau_1, \dots, \tau_n \rangle$, $\omega_1, \dots, \omega_k$ are as in the rule for $?\beta_1 \dots ?\beta_k \phi$. That is, the first position (from left to right) where β_i appears in $\langle \tau_1, \dots, \tau_n \rangle$ is the ω_i -th one.

Let us consider, for example, (5.73) (“What circled when.”).

$$(5.73) \quad ?_{maxl} e^v ?w^v \text{Past}[e^v, \text{circling}(w^v)]$$

Let us also assume that $\text{trans}(\text{Past}[e^v, \text{circling}(w^v)], \lambda_{init})$ returns (5.74). In this case, $\phi' = \text{Past}[e^v, \text{circling}(w^v)]$ and $\lceil \phi' \rceil = \langle e^v, w^v \rangle$. (5.74) shows all the combinations of *ets* and values of e^v and w^v , for which the denotation of $\text{Past}[e^v, \text{circling}(w^v)]$ is T . In each tuple, the value of the first explicit attribute (that corresponds to e^v) is the same as the time-stamp, because the semantics of *Past* requires the value of e^v to be the same as *et* (represented by the time-stamp). To save space, I omit the time-stamps.

(5.74)

[5:02pm 22/11/95, 5:17pm 22/11/95]	BA737	...
[5:05pm 22/11/95, 5:15pm 22/11/95]	BA737	...
[5:07pm 22/11/95, 5:13pm 22/11/95]	BA737	...
...
[4:57pm 23/11/95, 5:08pm 23/11/95]	BA737	...
[4:59pm 23/11/95, 5:06pm 23/11/95]	BA737	...
[5:01pm 23/11/95, 5:04pm 23/11/95]	BA737	...
...
[8:07am 22/11/95, 8:19am 22/11/95]	UK160	...
[8:08am 22/11/95, 8:12am 22/11/95]	UK160	...
[8:09am 22/11/95, 8:10am 22/11/95]	UK160	...
...

BA737 was circling from 5:02pm to 5:17pm on 22/11/95, and from 4:57pm to 5:08pm on 23/11/95. UK160 was circling from 8:07am to 8:19am on 22/11/95. (5.74) also contains tuples for the subperiods of these periods, because *circling*(w^v) (like all TOP predicates) is homogeneous (section 3.6). $\text{Past}[e^v, \text{circling}(w^v)]$ is true at all these subperiods that end before the present chronon.

In our example, the embedded SELECT statement of $\text{trans}(?\beta_1 ?\beta_2 ?\beta_3 \dots ?\beta_k \phi', \lambda_{init})$ is:

$$(5.75) \quad \begin{aligned} &(\text{SELECT DISTINCT 'dummy', t1.2} \\ &\quad \text{VALID t1.1} \\ &\quad \text{FROM trans(Past}[e^v, \text{circling}(w^v)], \lambda_{init}) \text{ AS t1}) \end{aligned}$$

(5.75) generates (5.76), where the time-stamps are the values of the first explicit attribute of (5.74) (i.e. they correspond to e^v). The ‘dummy’ in the embedded SELECT

statement ((5.75) in our example) means that the first explicit attribute of that statement's resulting relation should have the string “*dummy*” as its value in all tuples. This is needed when $k = 1$. If, for example, (5.73) were $?_{max} e^v \text{ Past}[e^v, \text{circling}(ba737)]$, without the ‘*dummy*’ the SELECT clause of (5.75) would contain nothing after DISTINCT (this is not allowed in TSQL2).

(5.76)

<i>dummy</i>	<i>BA737</i>	[5:02pm 22/11/95, 5:17pm 22/11/95]
<i>dummy</i>	<i>BA737</i>	[5:05pm 22/11/95, 5:15pm 22/11/95]
<i>dummy</i>	<i>BA737</i>	[5:07pm 22/11/95, 5:13pm 22/11/95]
...
<i>dummy</i>	<i>BA737</i>	[4:57pm 23/11/95, 5:08pm 23/11/95]
<i>dummy</i>	<i>BA737</i>	[4:59pm 23/11/95, 5:06pm 23/11/95]
<i>dummy</i>	<i>BA737</i>	[4:59pm 23/11/95, 5:06pm 23/11/95]
...
<i>dummy</i>	<i>UK160</i>	[8:07am 22/11/95, 8:19am 22/11/95]
<i>dummy</i>	<i>UK160</i>	[8:08am 22/11/95, 8:12am 22/11/95]
<i>dummy</i>	<i>UK160</i>	[8:09am 22/11/95, 8:10am 22/11/95]
...

The (NOSUBPERIOD) of the translation rule removes from (5.76) any tuples that do not correspond to maximal periods. That is (5.76) becomes (5.77).

(5.77)

<i>dummy</i>	<i>BA737</i>	[5:02pm 22/11/95, 5:17pm 22/11/95]
<i>dummy</i>	<i>BA737</i>	[4:57pm 23/11/95, 5:08pm 23/11/95]
<i>dummy</i>	<i>UK160</i>	[8:07am 22/11/95, 8:19am 22/11/95]

The overall (5.73) is mapped to (5.78), which generates (5.79). (5.79) represents the denotation of (5.73) w.r.t. $M(st)$ and st (pairs of maximal circling periods and the corresponding flights).

(5.78) (SELECT DISTINCT SNAPSHOT VALID(t2), t2.2
 FROM (SELECT DISTINCT 'dummy', t1.2
 VALID t1.1
 FROM *trans*(*Past*[e^v , *circling*(w^v)], λ_{init}) AS t1
) (NOSUBPERIOD) AS t2)

(5.79)

[5:02pm 22/11/95, 5:17pm 22/11/95]	<i>BA737</i>
[4:57pm 23/11/95, 5:08pm 23/11/95]	<i>BA737</i>
[8:07am 22/11/95, 8:19am 22/11/95]	<i>UK160</i>

Appendix A proves that the translation rules for wh-formulae satisfy theorem 5.1.

```

(SELECT DISTINCT SNAPSHOT t4.3
 FROM (SELECT DISTINCT VALID(t3), t3.1, t3.2, t3.3
       VALID VALID(t3)
       FROM (SELECT DISTINCT t1.1, t1.2, t1.3
             VALID PERIOD(BEGIN(VALID(t1)), END(VALID(t1)))
             FROM (SELECT DISTINCT insp.1, insp.2, insp.3
                   VALID VALID(insp)
                   FROM inspections(PERIOD) AS insp)(ELEMENT) AS t1,
             (SELECT DISTINCT SNAPSHOT inspcmpl.1, inspcmpl.2, inspcmpl.3
             FROM inspections AS inspcmpl
             WHERE inspcmpl.4 = 'complete') AS t2
       WHERE t1.1 = t2.1 AND t1.2 = t2.2
       AND t1.3 = t2.3 AND t1.3 = 'UK160'
       AND INTERSECT(
         INTERSECT(
           PERIOD(TIMESTAMP 'beginning', TIMESTAMP 'forever'),
           PERIOD 'today' - INTERVAL '1' DAY),
         PERIOD(TIMESTAMP 'beginning',
               TIMESTAMP 'now' - INTERVAL '1' MINUTE))
       CONTAINS PERIOD(BEGIN(VALID(t1)), END(VALID(t1)))
     ) AS t3
  ) AS t4)

```

Figure 5.3: Example of generated TSQL2 code

5.12 Optimising the generated TSQL2 code

The generated TSQL2 code is often verbose. There are usually ways in which it could be shortened and still return the same results. Figure 5.3, for example, shows the code that is generated by the translation of (5.80), if chronons correspond to minutes. ((5.80) expresses the reading of “*Who inspected UK160 yesterday?*” where the inspection must have both started and been completed on the previous day.)

$$(5.80) \quad ?w^v \text{ At}[\text{yesterday}, \text{Past}[e^v, \text{Culm}[\text{inspecting}(\text{occr}^v, w^v, \text{uk160})]]]$$

I assume here that $h'_{pfuns}(\text{inspecting}, 3)$ and $h'_{culms}(\text{inspecting}, 3)$ are (5.45) and (5.46) respectively. The embedded SELECT statements of figure 5.3 that are associated with **t1** and **t2** are (5.45) and (5.46). The embedded SELECT statement that is associated with **t3** corresponds to $\text{Culm}[\text{inspecting}(\text{occr}^v, w^v, \text{uk160})]$ (see the rule for $\text{Culm}[\pi(\tau_1, \dots, \tau_n)]$ in section 5.11). It generates a relation whose explicit attributes show all the combinations of codes, inspectors, and inspected objects that correspond to complete inspections. The time-stamps of this relation represent periods that cover whole inspections (from start to completion). The last constraint in the WHERE clause (the one with CONTAINS) admits only tuples whose time-stamps (whole inspections) are subperiods

of lt . The two nested INTERSECTS before CONTAINS represent lt . The At has narrowed lt to the intersection of its original value (whole time-axis) with the previous day (PERIOD 'today' - INTERVAL '1' DAY). The $Past$ has narrowed lt further to the intersection with $[t_{first}, st)$ (PERIOD(TIMESTAMP 'beginning', TIMESTAMP 'now' - INTERVAL '1' MINUTE)).

The embedded SELECT statement that is associated with τ_4 is generated by the translation rule for $Past[\beta, \phi']$ (section 5.11). It returns the same relation as the statement that is associated with τ_3 , except that the relation of τ_4 's statement has an additional explicit attribute that corresponds to the first argument of $Past$. In each tuple, the value of this extra attribute is the same as the time-stamp (et). The topmost SELECT clause projects only the third explicit attribute of the relation returned by τ_4 's statement (this attribute corresponds to w^v of (5.80)).

The code of figure 5.3 could be shortened in several ways. τ_4 's statement, for example, simply adds an extra attribute for the first argument of $Past$. In this particular case, this extra attribute is not used, because (5.80) contains no interrogative quantifier for the first argument of $Past$. Hence, τ_4 's statement could be replaced by τ_3 's (the topmost SELECT clause would have to become SELECT DISTINCT SNAPSHOT $\tau_3.2$). One could also drop the top-level SELECT statement, and replace the SELECT clause of τ_3 's statement with SELECT DISTINCT SNAPSHOT $\tau_1.2$. Furthermore, the intersection of the whole time-axis (PERIOD(TIMESTAMP 'beginning', TIMESTAMP 'forever')) with any period p is simply p . Hence, the second INTERSECT(... , ...) could be replaced by its second argument. The resulting code is shown in figure 5.4. Further simplifications are possible.

Most DBMSs employ optimisation techniques. A commercial DBMS supporting TSQL2 would probably be able to carry out at least some of the above simplifications. Hence, the reader may wonder why should the NLITDB attempt to optimise the TSQL2 code, rather than delegate the optimisation to the DBMS. First, as mentioned in section 1.2.4, only a prototype DBMS currently supports TSQL2. Full-scale TSQL2 DBMSs with optimisers may not appear in the near future. Second, long database language queries (like the ones generated by the framework of this thesis) can often confuse generic DBMS optimisers, causing them to produce inefficient code. Hence, shortening the TSQL2 code before submitting it to the DBMS is again important. It would be interesting to examine if optimisations like the ones discussed above could be automated, and

```

(SELECT DISTINCT SNAPSHOT t1.2
FROM (SELECT DISTINCT insp.1, insp.2, insp.3
      VALID VALID(insp)
      FROM inspections(PERIOD) AS insp)(ELEMENT) AS t1,
(SELECT SNAPSHOT inspcmpl.1, inspcmpl.2, inspcmpl.3
FROM inspections AS inspcmpl
WHERE inspcmpl.4 = 'complete') AS t2
WHERE t1.1 = t2.1 AND t1.2 = t2.2
AND t1.3 = t2.3 AND t1.3 = 'UK160'
AND INTERSECT(PERIOD 'today' - INTERVAL '1' DAY,
               PERIOD(TIMESTAMP 'beginning',
                      TIMESTAMP 'now' - INTERVAL '1' MINUTE))
CONTAINS PERIOD(BEGIN(VALID(t1)), END(VALID(t1)))

```

Figure 5.4: Shortened TSQL2 code

integrated into the framework of this thesis as an additional layer between the TOP to TSQL2 translator and the DBMS. I have not explored this issue.

5.13 Related work

Various mappings from forms of logic to and from relational algebra (e.g. [Ullman 88], [Van Gelder & Topor 91]), from logic programming languages to SQL (e.g. [Lucas 88], [Draxler 92]), and from logic formulae generated by NLIDBs to SQL ([Lowden *et al.* 91a], [Androutsopoulos 92], [Androutsopoulos *et al.* 93], [Rayner 93]) have been discussed in the past. The mapping which is most relevant to the TOP to TSQL2 translation of this chapter is that of [Boehlen *et al.* 96].

Boehlen *et al.* study the relation between TSQL2 and an extended version of first order predicate logic (henceforth called SUL), that provides the additional temporal operators \bullet (previous), \circ (next), **since**, and **until**. SUL is point-based, in the sense that SUL formulae are evaluated with respect to single time-points. SUL assumes that time is discrete. Roughly speaking, $\bullet\phi$ is true at a time-point t iff ϕ is true at the time-point immediately before t . Similarly, $\circ\phi$ is true at t iff ϕ is true at the time-point immediately after t . ϕ_1 **since** ϕ_2 is true at t iff there is some t' before t , such that ϕ_2 is true at t' , and for every t'' between t' and t , ϕ_1 is true at t'' . Similarly, ϕ_1 **until** ϕ_2 is true at t iff there is some t' after t , such that ϕ_2 is true at t' , and for every t'' between t and t' , ϕ_1 is true at t'' . Various other operators are also defined, but these are all definable in terms of \bullet , \circ , **since**, and **until**. For example, $\Diamond\phi$ is equivalent to *true* **since** ϕ (*true* is a special formula that is true at all time-points). In effect, $\Diamond\phi$ is

true at t if there is a t' before t , and ϕ is true at t' . For example, (5.81) and (5.83) can be expressed as (5.82) and (5.84) respectively.

(5.81) BA737 departed (at some past time).

(5.82) $\Diamond \text{depart}(\text{ba737})$

(5.83) Tank 2 has been empty (all the time) since BA737 departed.

(5.84) $\text{empty}(\text{tank2}) \text{ since } \text{depart}(\text{ba737})$

Boehlen et al. provide rules that translate from SUL to TSQL2. (They also show how to translate from a fragment of TSQL2 back to SUL, but this direction is irrelevant here.) The underlying ideas are very similar to those of this chapter. Roughly speaking, there are non-recursive rules for atomic formulae, and recursive rules for non-atomic formulae. For example, the translation rule for ϕ_1 **since** ϕ_2 calls recursively the translation algorithm to translate ϕ_1 and ϕ_2 . The result is a **SELECT** statement, that contains two embedded **SELECT** statements corresponding to ϕ_1 and ϕ_2 . Devising rules to map from SUL to TSQL2 is much easier than in the case of TOP, mainly because SUL formulae are evaluated with respect to only one time-parameter (TOP formulae are evaluated with respect to three parameters, *st*, *et*, and *lt*), SUL is point-based (TOP is period-based; section 3.1), and SUL provides only four temporal operators whose semantics are very simple (the TOP version of this chapter has eleven operators, whose semantics are more complex). Consequently, proving the correctness of the SUL to TSQL2 mapping is much simpler than in the case of TOP.

It has to be stressed, however, that TOP and SUL were designed for very different purposes. SUL is interesting from a theoretical temporal-logic point of view. Roughly speaking, it has been proven that whatever can be expressed in traditional first-order predicate logic with a temporal precedence connective by treating time as an extra predicate argument (e.g. (1.12) of page 6) can also be expressed in first-order predicate logic enhanced with only a **since** and an **until** operator, subject to some continuity conditions (the reverse is not true; see chapter II.2 of [vanBenthem 83]). The mapping from SUL to TSQL2 (and the reverse mapping from a fragment of TSQL2 to SUL) is part of a study of the relative expressiveness of SUL and TSQL2. The existence of a mapping from SUL to TSQL2 shows that TSQL2 is at least as expressive as SUL. (The reverse is not true. Full TSQL2 is more expressive than SUL; see [Boehlen *et al.* 96].)

In contrast, TOP was not designed to study expressiveness issues, but to facilitate

the mapping from (a fragment of) English to logical form. Chapter 4 showed how to translate systematically from a non-trivial fragment of English temporal questions into TOP. No such systematic translation has been shown to exist in the case of SUL, and it is not at all obvious how temporal English questions (e.g. containing progressive and perfect tenses, temporal adverbials, temporal subordinate clauses) could be mapped systematically to appropriate SUL formulae.

Although the study of expressiveness issues is not a goal of this thesis, I note that the TOP to TSQL2 translation of this chapter implies that TSQL2 is at least as expressive as TOP (every TOP formula can be mapped to an appropriate TSQL2 query). The reverse is not true: it is easy to think of TSQL2 queries (e.g. queries that report cardinalities of sets) that cannot be expressed in (the current version of) TOP. Finally, neither TOP nor SUL can be said to be more expressive than the other, as there are English sentences that can be expressed in SUL but not TOP, and vice-versa. For example, the SUL formula (5.84) expresses (5.83), a sentence that cannot be expressed in TOP. Also, the TOP formula (5.86) expresses (5.85). There does not seem to be any way to express (5.85) in SUL.

(5.85) Tank 2 was empty for two hours.

(5.86) $For[hour^c, 2, Past[e^v, empty(tank2)]]$

5.14 Summary

TSQL2 is an extension of SQL-92 that provides special facilities for manipulating temporal information. Some modifications of TSQL2 were adopted in this chapter. Some of these are minor, and were introduced to bypass uninteresting details (e.g. referring to explicit attributes by number) or obscure points in the TSQL2 definition (e.g. the new version of the INTERVAL function). Other modifications are more significant, and were introduced to facilitate the TOP to TSQL2 translation (e.g. (SUBPERIOD) and (NOSUBPERIOD)). One of these more significant modifications (calendric relations) is generally useful. Some minor modifications of TOP were also adopted in this chapter.

A method to translate from TOP to TSQL2 was framed. Each TOP formula ϕ is mapped to a TSQL2 query. This is executed by the DBMS, generating a relation that represents (via an interpretation function) $\|\phi\|^{M(st),st}$. Before the translation method can be used, the configurer of the NLITDB must specify some functions (h'_{cons} , h'_{pfuns} ,

$h'_{culms}, h'_{gparts}, h'_{cparts}$) that link certain basic TOP expressions to TSQL2 expressions. The TOP to TSQL2 translation is then carried out by a set of translation rules. The rules have to satisfy two theorems (5.1 and 5.2) for the translation to be correct (i.e. for the TSQL2 query to generate a relation that represents $\|\phi\|^{M(st),st}$). An informal description of the functionality of some of the rules was given. The full set of the translation rules, along with a proof that they satisfy theorems 5.1 and 5.2, is given in appendix A. Further work could explore how to optimise the generated TSQL2 code.

The TOP to TSQL2 translation is in principle similar to the SUL to TSQL2 translation of [Boehlen *et al.* 96]. TOP and SUL, however, were designed for very different purposes, and the SUL to TSQL2 translation is much simpler than the TOP to TSQL2 one.

Chapter 6

The prototype NLITDB

“Time works wonders.”

6.1 Introduction

This chapter discusses the architecture of the prototype NLITDB, provides some information on how the modules of the system were implemented, and explains which modules would have to be added if the prototype NLITDB were to be used in real-life applications. A description of the hypothetical airport database is also given, followed by sample questions from the airport domain and the corresponding output of the NLITDB. The chapter ends with information on the speed of the system.

6.2 Architecture of the prototype NLITDB

Figure 6.1 shows the architecture of the prototype NLITDB. Each English question is first parsed using the HPSG grammar of chapter 4, generating an HPSG sign. Multiple signs are generated for questions that the parser understands to be ambiguous. A TOP formula is then extracted from each sign, as discussed in section 4.6. Each extracted formula subsequently undergoes the post-processing of section 4.17. (The post-processor also converts the formulae from the TOP version of chapters 3 and 4 to the version of 5; see section 5.5.) As discussed in section 4.17, the post-processing sometimes generates multiple formulae from the same original formula.

Each one of the formulae that are generated at the end of the post-processing captures what the NLITDB understands to be a possible reading of the English question. Many

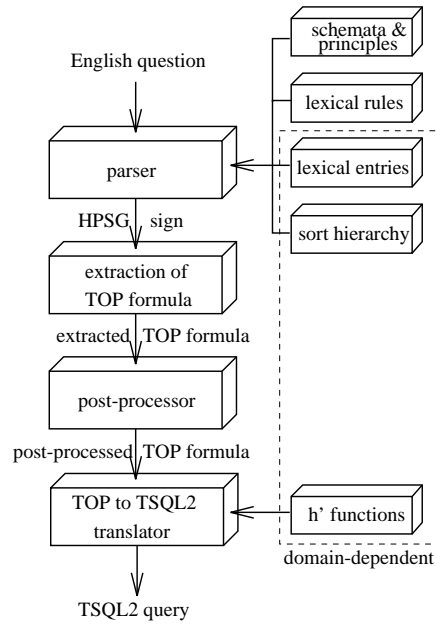


Figure 6.1: Architecture of the prototype NLITDB

fully-fledged NLIDBs use preference measures to guess which reading among the possible ones the user had in mind, or generate “unambiguous” English paraphrases of the possible readings, asking the user to select one (see [Alshawi 92], [Alshawi *et al.* 92], [De Roeck & Lowden 86] and [Lowden & De Roeck 86]). No such mechanism is currently present in the prototype NLITDB. All the formulae that are generated at the end of the post-processing are translated into TSQL2. The NLITDB prints all the resulting TSQL2 queries along with the corresponding TOP formulae. The TSQL2 queries would be executed by the DBMS to retrieve the information requested by the user. As mentioned in section 1.2.4, however, the prototype NLITDB has not been linked to a DBMS. Hence, the TSQL2 queries are currently not executed, and no answers are produced.

The following sections provide more information about the grammar and parser, the module that extracts TOP formulae from HPSG signs, the post-processor, and the TOP to TSQL2 translator.

6.3 The grammar and parser

The HPSG version of chapter 4 was coded in the formalism of ALE [Carpenter 92] [Carpenter & Penn 94], building on previous ALE encodings of HPSG fragments by

Gerald Penn, Bob Carpenter, Suresh Manandhar, and Claire Grover.¹ ALE can be thought of as a grammar-development environment. It provides a chart parser (which is the one used in the prototype NLITDB; see [Gazdar & Mellish 89] for an introduction to chart parsers) and a formalism that can be used to write unification-grammars based on feature structures.

Coding the HPSG version of chapter 4 in ALE’s formalism proved straight-forward. ALE’s formalism allows one to specify grammar rules, definite constraints (these are similar to Prolog rules, except that predicate arguments are feature structures), lexical entries, lexical rules, and a hierarchy of sorts of feature structures. The schemata and principles of the HPSG version of chapter 4 were coded using ALE grammar rules and definite constraints. ALE’s lexical entries, lexical rules, and sort hierarchy were used to code HPSG’s lexical signs, lexical rules, and sort hierarchy respectively.

The ALE grammar rules and definite constraints that encode the HPSG schemata and principles are domain-independent, i.e. they require no modifications when the NLITDB is configured for a new application domain. The lexical rules of the prototype NLITDB are also intended to be domain-independent, though their morphology parts need to be extended (e.g. more information about the morphology of irregular verbs is needed) before they can be used in arbitrary application domains. The lexical entries of the system that correspond to determiners (e.g. “a”, “some”), auxiliary verbs, interrogative words (e.g. “who”, “when”), prepositions, temporal subordinators (e.g. “while”, “before”), month names, day names, etc. (e.g. “January”, “Monday”) are also domain-independent. The person configuring the NLITDB, however, needs to provide lexical entries for the nouns, adjectives, and (non-auxiliary) verbs that are used in the particular application domain (e.g. “flight”, “open”, “to land”). The largest part of the NLITDB’s sort hierarchy is also domain independent. Two parts of it need to be modified when the system is configured for a new domain: the hierarchy of world entities that is mounted under *ind* (section 4.4 and figure 4.4 on page 126), and the subsorts of *predicate* that correspond to TOP predicates used in the domain (section 4.3 and figure 4.1 on page 122). As will be discussed in section 6.6, tools could be added to help the configurator modify the domain-dependent modules.

¹ The prototype NLITDB was implemented using ALE version 2.0.2 and Sicstus Prolog version 2.1.9. Chris Brew provided additional ALE code for displaying feature structures. The software of the prototype NLITDB, including the ALE grammar, is available from http://www.dai.ed.ac.uk/groups/nlp/NLP_home_page.html. An earlier version of the prototype NLITDB was implemented using the HPSG-PL and PLEUK systems [Popowich & Vogel 91] [Calder *et al.* 94].

6.4 The extractor of TOP formulae and the post-processor

The module that extracts TOP formulae from HPSG signs actually generates TOP formulae written as Prolog terms. For example, it generates (6.2) instead of (6.1). The correspondence between the two notations should be obvious. The Prolog-like notation of (6.2) is also used in the formulae that are passed to the TOP to TSQL2 translator, and in the output of the NLITDB (see section 6.8 below).

$$(6.1) \quad ?x1^v \text{ Ntense}[x3^v, \text{president}(x1^v)] \wedge \text{Past}[x2^v, \text{located_at}(x1^v, \text{terminal2})]$$

$$(6.2) \quad \text{interrog}(\text{x1}^v, \text{and}(\text{ntense}(\text{x3}^v, \text{president}(\text{x1}^v)), \\ \text{past}(\text{x2}^v, \text{located_at}(\text{x1}^v, \text{terminal2}))))$$

The extractor of the TOP formulae is implemented using Prolog rules and ALE definite constraints (Prolog-like rules whose predicate-arguments are feature structures). Although the functionality of the extractor's code is simple, the code itself is rather complicated (it has to manipulate the internal data structures that ALE uses to represent feature structures) and will not be discussed.

As mentioned in section 6.2, the post-processor of figure 6.1 implements the post-processing phase of section 4.17. The post-processor also eliminates *Part* operators by merging them with the corresponding *At*, *Before*, or *After* operators, to convert the formulae into the TOP version of the TOP to TSQL2 translator (section 5.5). The post-processor's code, which is written in Prolog, presents no particular interest and will not be discussed.

6.5 The TOP to TSQL2 translator

Implementing in Prolog the TOP to TSQL2 mapping of chapter 5 proved easy. The code of the TOP to TSQL2 translator of figure 6.1 is basically a collection of Prolog rules for the predicate `trans`. Each one of these rules implements one of the translation rules of section 5.11 and appendix A. For example, the following Prolog rule implements the translation rule for $\text{Past}[\beta, \phi']$ (p. 239). (I omit some uninteresting details of the actual Prolog rule.)

```
trans(past(_^v, PhiPrime), Lambda, Sigma):-
    chronons(Chronon),
    multiappend([
```



```

    "INTERSECT(", Lambda, ", ",
        "PERIOD(TIMESTAMP 'beginning', ",
            "TIMESTAMP 'now' - INTERVAL '1' ", Chronon, ")"))"
], LambdaPrime),
trans(PhiPrime, LambdaPrime, SigmaPrime),
new_cn(Alpha),
corners(PhiPrime, CList),
length(CList, N),
generate_select_list(Alpha, N, SelectList),
multiappend([
    "(SELECT DISTINCT VALID(", Alpha, "), ", SelectList,
    "VALID VALID(", Alpha, ")",
    "FROM ", SigmaPrime, " AS ", Alpha, ")",
], Sigma).

```

The first argument of `trans` is the TOP formula to be translated (in the notation of (6.2)). `Lambda` is a string standing for the λ argument of the *trans* function of section 5.10 (initially "PERIOD(TIMESTAMP 'beginning', TIMESTAMP 'forever')"). The generated TSQL2 code is returned as a string in `Sigma`.

The `chronons(Chronon)` causes `Chronon` to become a string holding the TSQL2 name of the granularity of chronons (e.g. "MINUTE"). The `chronons` predicate is supplied by the configurer of the NLITDB, along with Prolog predicates that define the h' functions of section 5.9. For example, the following predicate defines $h'_{pfuns}(inspecting, 3)$ to be the SELECT statement of (5.45) on page 228. The `chronons` predicate and the predicates that define the h' functions are the only domain-dependent parts of the TOP to TSQL2 translator.

```

h_prime_pfun_map(inspecting, 3,
["SELECT DISTINCT insp.1, insp.2, insp.3",
 "VALID VALID(insp)",
 "FROM inspections(PERIOD) AS insp"]]).

```

The first `multiappend` in the *trans* rule above generates the λ' string of the translation rule for $Past[\beta, \phi']$ (p. 239). It concatenates the string-elements of the list provided as first argument to `multiappend`, and the resulting string (λ') is returned in `LambdaPrime`. As in the translation rule for $Past[\beta, \phi']$, the translation mapping is then invoked recursively to translate ϕ' (`PhiPrime`). The result of this translation is stored in `SigmaPrime`.

`new_cn(Alpha)` returns in `Alpha` a string holding a new correlation name (`new_cn` implements the correlation names generator of section 5.11). The `corners(PhiPrime,`

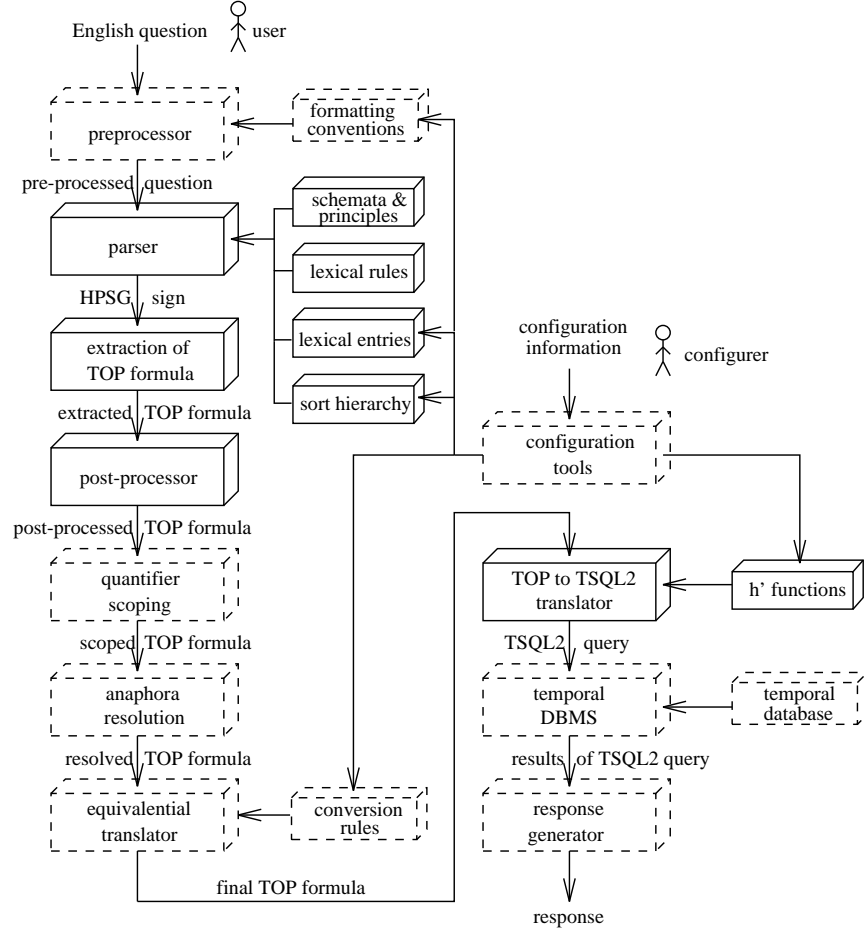


Figure 6.2: Extended architecture of the prototype NLITDB

`CList`) causes `CList` to become $\lceil \phi' \rceil$, and `length(CList, N)` returns in `N` the length of $\lceil \phi' \rceil$. The `generate_select_list(Alpha, N, SelectList)` returns in `SelectList` a string of the form `Alpha.1, Alpha.2, ..., Alpha.N`. Finally, the second `multiappend` returns in `Sigma` a string that holds the overall TSQL2 code.

6.6 Modules to be added

The prototype NLITDB is intended to demonstrate that the mappings from English to TOP and from TOP to TSQL2 are implementable. Consequently, the architecture of the prototype NLITDB is minimal. Several modules, to be sketched in the following sections, would have to be added if the system were to be used in real-life applications. Figure 6.2 shows how these modules would fit into the existing system architecture.

(Modules drawn with dashed lines are currently not present.)

6.6.1 Preprocessor

The ALE parser requires its input sentence to be provided as a Prolog list of symbols (e.g. (6.3)).

(6.3) `[was,ba737,circling,at,pm5_00]`

As there is essentially no interface between the user and the ALE parser in the prototype NLITDB, English questions have to be typed in this form. This does not allow words to start with capital letters or numbers, or to contain characters like “/” and “:” (Prolog symbols cannot contain these characters and must start with lower case letters). To bypass these constraints, proper names, dates, and times currently need to be typed in unnatural formats (e.g. “london”, “d1_5_92”, “pm5_00”, “y1991” instead of “London”, “1/5/92” “5:00pm”, “1991”).

A preprocessing module is needed, that would allow English questions to be typed in more natural formats (e.g. (6.4)), and would transform the questions into the format required by the parser (e.g. (6.3)).

(6.4) Was BA737 circling at 5:00pm?

Similar preprocessing modules are used in several natural language front-ends (e.g. CLE [Alshawhi 92] and MASQUE [Lindop 86]). These modules typically also merge parts of the input sentence that need to be processed as single words. For example, the lexicon of the airport domain has a single lexical entry for “gate 2”. The preprocessor would merge the two words of “gate 2” in (6.5), generating (6.6). (Currently, “gate 2” has to be typed as a single word.)

(6.5) Which flights departed from gate 2 yesterday?

(6.6) `[which,flights,departed,from,gate2,yesterday]`

The preprocessing modules typically also handle proper names that cannot be included in the lexicon because they are too many, or because they are not known when creating the lexicon. In a large airport, for example, there would be hundreds of flight names (“BA737”, “UK1751”, etc.). Having a different lexical entry for each flight name is

impractical, as it would require hundreds of entries to be added into the lexicon. Also, new flights (and hence flight names) are created occasionally, which means that the lexicon would have to be updated whenever a new flight is created. Instead, the lexicon could contain entries for a small number of pseudo-flight names (e.g. “*flight_name1*”, “*flight_name2*”, . . . , “*flight_nameN*”; *N* is the maximum number of flight names that may appear in a question, e.g. 5). Each one of these lexical entries would map a pseudo-flight name to a TOP constant (e.g. *flight1*, *flight2*, . . . , *flightN*).² The preprocessor would use domain-dependent formatting conventions to identify flight names in the English question (e.g. that any word that starts with two or three capital letters and is followed by three or four digits is a flight name). Each flight name in the question would be replaced by a pseudo-flight name. For example, the preprocessor would turn (6.7) into (6.8).

(6.7) Did BA737 depart before UK160 started to land?

(6.8) [did,flight_name1,depart,before,flight_name2,started,to,land]

(6.8) would then be parsed, giving rise to (6.9) (*flight1* and *flight2* are TOP constants introduced by the lexical entries of “*flight_name1*” and “*flight_name2*”). An extra step would be added to the post-processing phase of section 4.17, to substitute *flight1* and *flight2* with TOP constants that reflect the original flight names. For example, the preprocessor could pass to the post-processor the original flight names (“BA737” and “UK160”), and the post-processor could replace *flight1* and *flight2* by the original flight names in lower case. This would cause (6.9) to become (6.10). Similar problems arise in the case of dates, times, numbers, etc.

(6.9) Before[Past[e1^v, Begin[landing(*flight2*)]], Past[e2^v, depart(*flight1*)]]

(6.10) Before[Past[e1^v, Begin[landing(uk160)]], Past[e2^v, depart(ba737)]]

No preprocessing mechanism is currently present in the prototype NLITDB. The lexicon contains (for demonstration purposes) only a few entries for particular (not pseudo-) flight names, times, dates, and numbers (e.g. “BA737”, “9:00am”). For example, there is no entry for “9:10am”. This causes the parsing of “Which tanks were empty at 9:10am?” to fail. In contrast the parsing of “Which tanks were empty at 9:00am?” succeeds, because there *is* a lexical entry for “9:00am”.

² In the HPSG grammar of chapter 4, these constants would be represented using sorts like *flight1*, *flight2*, . . . , *flightN*, which would be daughters of *flight_ent* and sisters of *flight_ent_var* in figure 4.4 on page 126.

6.6.2 Quantifier scoping

When both words that introduce existential quantification (e.g. “a”, “some”) and words that introduce universal quantification (e.g. “every”, “each”) are allowed, it is often difficult to decide which quantifiers should be given scope over which other quantifiers. For example, (6.11) has two possible readings. Ignoring the temporal information of (6.11), these readings would be expressed in the traditional first-order predicate logic (FOPL) using formulae like (6.12) and (6.13).

(6.11) A guard inspected every gate.

(6.12) $\exists x (guard(x) \wedge \forall y (gate(y) \rightarrow inspect(x, y)))$

(6.13) $\forall y (gate(y) \rightarrow \exists x (guard(x) \wedge inspect(x, y)))$

In (6.12), the existential quantifier (introduced by “a”) is given wider scope over the universal one (introduced by “every”). According to (6.12), all the gates were inspected by the same guard. In contrast, in (6.13) where the universal quantifier is given wider scope over the existential one, each gate was inspected by a possibly different guard.

In (6.11), both scopings seem possible (at least in the absence of previous context). In many cases, however, one of the possible scopings is the preferred one, and there are heuristics to determine this scoping (see chapter 8 of [Alshawi 92]). For example, universal quantifiers introduced by “each” tend to have wider scope over existential quantifiers (e.g. if the “every” of (6.11) is replaced by “each”, the scoping of (6.13) becomes more likely than that of (6.12)).

In this thesis, words that introduce universal quantifiers were deliberately excluded from the linguistic coverage (section 2.13). This leaves only existential quantification and by-passes the quantifier scoping problem, because if all quantifiers are existential ones, the relative scoping of the quantifiers does not matter. (In TOP, existential quantification is expressed using free variables. There are also interrogative and interrogative-maximal quantifiers, but these are in effect existential quantifiers that have the additional side-effect of including the values of their variables in the answer.)

If the linguistic coverage of the prototype NLITDB were to be extended to support words that introduce universal quantification, an additional scoping module would have to be added (figure 6.2). The input to that module would be an “underspecified” TOP formula (see the discussion in chapter 2 of [Alshawi 92]), a formula that would not

specify the exact scope of each quantifier. In a FOPL-like formalism, an underspecified formula for (6.11) could look like (6.14).

$$(6.14) \quad inspect((\exists x \text{ guard}(x)), (\forall y \text{ gate}(y)))$$

The scoping module would generate all the possible scopings, and determine the most probable ones, producing formulae where the scope of each quantifier is explicit (e.g. (6.12) or (6.13)). Alternatively, one could attempt to use the the HPSG quantifier scoping mechanism (see [Pollard & Sag 94] and relevant comments in section 4.3) to reason about the possible scopings during the parsing. That mechanism, however, is a not yet fully developed part of HPSG.

6.6.3 Anaphora resolution

As discussed in sections 1.4 and 2.12, nominal anaphora (e.g. “*she*”, “*his salary*”) and most cases of temporal anaphora (e.g. “*in January*”, tense anaphora) are currently not supported. An anaphora resolution module would be needed if phenomena of this kind were to be supported. As in the case of quantifier scoping, I envisage a module that would accept “underspecified” TOP formulae, formulae that would not name explicitly the entities or times to which anaphoric expressions refer (figure 6.2). The module would determine the most probable referents of these expressions, using a discourse model that would contain descriptions of previously mentioned entities and times, information showing in which segments of the previous discourse the entities or times were mentioned, etc. (see [Barros & De Roeck 94] for a description of a similar module). The output of this module would be a formula that names explicitly the referents of anaphoric expressions.

6.6.4 Equivalential translator

The translation from TOP to TSQL2 of chapter 5 assumes that each pair $\langle \pi, n \rangle$ of a TOP predicate functor π and an arity n can be mapped to a valid-time relation (stored directly in the database, or computed from information in the database) that shows the event times where $\pi(\tau_1, \dots, \tau_n)$ is true, for all the possible world entities denoted by the TOP terms τ_1, \dots, τ_n . The configurer of the NLITDB specifies this mapping when defining h'_{pfun} (section 5.9). Although the assumption that each $\langle \pi, n \rangle$ can be mapped to a suitable relation is valid in most situations, there are cases where this assumption

does not hold. The “doctor on board” problem [Rayner 93] is a well-known example of such a case.

Let us imagine a database that contains only the following coalesced valid-time relation, that shows the times when a (any) doctor was on board each ship of a fleet.

<i>doctor_on_board</i>	
<i>ship</i>	
<i>Vincent</i>	[8:30am 22/1/96 – 11:45am 22/1/96] \cup [3:10pm 23/1/96 – 5:50pm 23/1/96] \cup [9:20am 24/1/96 – 2:10pm 24/1/96]
<i>Invincible</i>	[8:20am 22/1/96 – 10:15am 22/1/96] \cup [1:25pm 23/1/96 – 3:50pm 23/1/96]
...	...

Let us also consider a question like (6.15), which would be mapped to the TOP formula (6.16). I assume here that “*doctor*” and “*ship*” introduce predicates of the form *doctor*(τ_1) and *ship*(τ_2), and that the predicative preposition “*on*” introduces a predicate of the form *located_on*(τ_3, τ_4) ($\tau_1, \dots, \tau_4 \in TERMS$). For simplicity, I assume that “*doctor*” and “*ship*” do not introduce *Ntense* operators (section 4.9.1).

(6.15) Is there a doctor on some ship?

(6.16) $doctor(d^v) \wedge ship(s^v) \wedge Pres[located_on(d^v, s^v)]$

To apply the TOP to TSQL2 translation method of chapter 5, one needs to map $\langle doctor, 1 \rangle$ to a valid-time relation (computed from information in the database) that shows the event times where *doctor*(τ_1) is true, i.e. when the entity denoted by τ_1 was a doctor. Unfortunately, the database (which contains only *doctor_on_board*) does not show when particular entities were doctors, and hence such a relation cannot be computed. In the same manner, $\langle ship, 1 \rangle$ has to be mapped to a relation that shows the ships that existed at each time. This relation cannot be computed: *doctor_on_board* does not list all the ships that existed at each time; it shows only ships that had a doctor on board at each time. Similarly, $\langle located_on, 2 \rangle$ has to be mapped to a relation that shows when *located_on*(τ_3, τ_4) is true, i.e. when the entity denoted by τ_3 was on the entity denoted by τ_4 . Again, this relation cannot be computed. If, for example, τ_3 denotes a doctor (e.g. Dr. Adams) and τ_4 denotes Vincent, there is no way to find out when that particular doctor was on Vincent: *doctor_on_board* shows only when some (any) doctor was on each ship; it does not show when particular doctors (e.g. Dr. Adams) were on each ship. Hence, the translation method of chapter 5 cannot be used.

It should be easy to see, however, that (6.16) is equivalent to (6.17), if $doctor_on_ship(\tau_5)$ is true at event times where the entity denoted by τ_5 is a ship, and a doctor of that time is on that ship. What is interesting about (6.17) is that there *is* enough information in the database to map $\langle doctor_on_ship, 1 \rangle$ to a relation that shows the event times where $doctor_on_ship(\tau_5)$ holds. Roughly speaking, one simply needs to map $\langle doctor_on_ship, 1 \rangle$ to the $doctor_on_board$ relation. Hence, the TOP to TSQL2 translation method of chapter 5 *can* be applied to (6.17), and the answer to (6.15) can be found by evaluating the resulting TSQL2 code.

$$(6.17) \quad Pres[doctor_on_ship(s^v)]$$

The problem is that (6.15) cannot be mapped directly to (6.17): the English to TOP mapping of chapter 4 generates (6.16). We need to convert (6.16) (whose predicates are introduced by the lexical entries of nouns, prepositions, etc.) to (6.17) (whose predicates are chosen to be mappable to relations computed from information in the database). An “equivalential translator” similar to the “abductive equivalential translator” of [Rayner 93] and [Alshawhi *et al.* 92] could be used to carry out this conversion. Roughly speaking, this would be an inference module that would use domain-dependent conversion rules, like (6.18) which allows any formula of the form $doctor(\tau_1) \wedge ship(\tau_2) \wedge Pres[located_on(\tau_1, \tau_2)]$ ($\tau_1, \tau_2 \in TERMS$) to be replaced by $Pres[doctor_on_ship(\tau_2)]$. (6.18) would license the conversion of (6.16) into (6.17).

$$(6.18) \quad doctor(\tau_1) \wedge ship(\tau_2) \wedge Pres[located_on(\tau_1, \tau_2)] \equiv Pres[doctor_on_ship(\tau_2)]$$

There would be two kinds of pairs $\langle \pi, n \rangle$ (π is a predicate functor and n an arity): pairs that are mapped to relations, and pairs for which this mapping is impossible (the value of h'_{pfun} would be undefined for the latter). The formula generated after the scoping and anaphora resolution would be passed to the equivalential translator (figure 6.2). If all the predicate functors and arities in the formula are among the pairs that are mapped to relations, the equivalential translator would have no effect. Otherwise, the equivalential translator would attempt to convert the formula into another one that contains only predicate functors and arities that are mapped to relations (an error would be reported if the conversion is impossible). The new formula would then be passed to the TOP to TSQL2 translator.

6.6.5 Response generator

The execution of the TSQL2 code produces the information that is needed to answer the user’s question. A response generator is needed to report this information to the user. In the simplest case, if the question is a yes/no one, the response generator would simply print a “yes” or “no”, depending on whether or not the TSQL2 code retrieved at least one tuple (section 5.10). Otherwise, the response generator would print the tuples retrieved by the TSQL2 code.

Ideally, the response generator would also attempt to provide *cooperative responses* (section 1.4; see also section 8.2 below). In (6.19), for example, if BA737 is at gate 4, the response generator would produce (6.20) rather than a simple “no”. That is, it would report the answer to (6.19) along with the answer to (6.21).

(6.19) Is BA737 at gate 2?

(6.20) No, BA737 is at gate 4.

(6.21) Which gate is BA737 at?

In that case, the architecture of the NLITDB would have to be more elaborate than that of figure 6.2, as the response generator would have to submit questions (e.g. (6.21)) on its own, in order to collect the additional information that is needed for the cooperative responses.

6.6.6 Configuration tools

As already noted, there are several parts of the prototype NLITDB that need to be modified whenever the NLITDB is configured for a new application. Most large-scale NLITDBs provide tools that automate these modifications, ideally allowing people that are not aware of the details of the NLITDB’s code to configure the system (see section 6 of [Androutsopoulos *et al.* 95b], and chapter 11 of [Alshawi 92]). A similar tool is needed in the prototype NLITDB of this thesis. Figure 6.2 shows how this tool would fit into the NLITDB’s architecture.³

³ Some of the heuristics of the quantifier scoping module and parts of the anaphora resolution module may in practice be also domain-dependent. In that case, parts of these modules would also have to be modified during the configuration. For simplicity, this is not shown in figure 6.2.

```

gates(gate, availability)
runways(runway, availability)
queues(queue, runway)
servicers(servicer)
inspectors(inspector)
sectors(sector)
flights(flight)
tanks(tank, content)
norm_departures(flight, norm_dep_time, norm_dep_gate)
norm_arrivals(flight, norm_arr_time, norm_arr_gate)
norm_servicer(flight, servicer)
flight_locations(flight, location)
circling(flight)
inspections(code, inspector, inspected, status)
services(code, servicer, flight, status)
boardings(code, flight, gate, status)
landings(code, flight, runway, status)
takeoffs(code, flight, runway, status)
taxiings(code, flight, origin, destination, status)

```

Figure 6.3: Relations of the airport database

6.7 The airport database

This section provides more information about the hypothetical airport database, for which the prototype NLITDB was configured.

The airport database contains nineteen relations, all valid-time and coalesced (section 5.2.3). Figure 6.3 shows the names and explicit attributes of the relations. For simplicity, I assume that the values of all the explicit attributes are strings. I also assume that chronons correspond to minutes, and that the *gregorian* calendric relation of section 5.3.3 is available. The *runways* relation has the following form:

<i>runways</i>		
<i>runway</i>	<i>availability</i>	
<i>runway1</i>	<i>open</i>	[8:00am 1/1/96, 7:30pm 3/1/96] ∪ [6:00am 4/1/96, 2:05pm 8/1/96] ∪ ...
<i>runway1</i>	<i>closed</i>	[7:31pm 3/1/96, 5:59am 4/1/96] ∪ [2:06pm 8/1/96, 5:45pm 8/1/96]
<i>runway2</i>	<i>open</i>	[5:00am 1/1/96, 9:30pm 9/1/96] ∪ ...
<i>runway2</i>	<i>closed</i>	[9:31pm 9/1/96, 10:59am 10/1/96] ∪ ...

The *availability* values are always *open* or *closed*. There are two tuples for each runway: one showing the times when the runway was open, and one showing the times when it

was closed. If a runway did not exist at some time (e.g. a runway may not have been constructed yet at that time), both tuples of that runway exclude this time from their time-stamps. The *gates* relation is similar. Its *availability* values are always *open* or *closed*, and there are two tuples for each gate, showing the times when the gate was open (available) or closed (unavailable) respectively.

Runways that are used for landings or take-offs have queues, where flights wait until they are given permission to enter the runway. The *queues* relation lists the names of the queues that exist at various times, along with the runways where the queues lead to. The *servicers* relation shows the names of the servicing companies that existed at any time. The *inspectors*, *sectors*, and *flights* relations are similar. The *tanks* relation shows the contents (*water*, *foam*, etc., or *empty* if the tank was empty) of each tank at every time where the tank existed.

Each outgoing flight is assigned a normal departure time and gate (see also section 2.4.5). The *norm_departures* relation shows these times and gates. For example, if *norm_departures* were as follows, this would mean that from 9:00am on 1/1/92 to 5:30pm on 31/11/95 BA737 normally departed each day from gate 2 at 2:05pm. (For simplicity, I assume that all flights are daily.) At 5:31pm on 31/11/95, the normal departure time of BA737 was changed to 2:20pm, while the normal departure gate remained gate 2. No further change to the normal departure time or gate of BA737 was made since then.

<i>norm_departures</i>			
<i>flight</i>	<i>norm_dep_time</i>	<i>norm_dep_gate</i>	
BA737	2:05pm	gate2	[9:00am 1/1/92, 5:30pm 31/11/95]
BA737	2:20pm	gate2	[5:31pm 31/11/95, now]

Similarly, each incoming flight is assigned a normal arrival time and a gate, listed in *norm_arrivals*. Flights are also assigned normal servicers, servicing companies that over a period of time normally service the flights whenever they arrive or depart. This information is stored in *norm_servicer*. The *flight_locations* relation shows the location of each flight over the time. Possible *location* values are the names of airspace sectors, gates, runways, or queues of runways. The *circling* relation shows the flights that were circling at each time.

As discussed in section 2.4.5, flights, gates, and runways are occasionally inspected. The *inspections* relation was discussed in section 5.9. It shows the inspection code, inspector, inspected object, status (completed or not), and time of each inspection.

The *services*, *boardings*, *landings*, *takeoffs*, and *taxiings* relations are very similar. They provide information about actual services, boardings, landings, take-offs, and taxiings from one location (*origin*) to another (*destination*). Each service, boarding, landing, take-off, or taxiing is assigned a unique code, stored in the *code* attribute. The *status* attribute shows if the climax is reached at the latest time-point of the time-stamp. The values of the *origin* and *destination* attributes of *taxiings* are names of gates, runways, and queues.

Apart from relations, a database would in practice also contain *integrity constraints* (see [Gertz & Lipect 95] and [Wijsen 95]). There would be, for example, a constraint saying that if the *circling* relation shows a flight as circling at some time, the *flights* relation must show that flight as existing at the same time. I do not discuss integrity constraints, as they are not directly relevant to this thesis.

6.8 Sample questions and output

This section presents sample questions from the airport domain, along with the corresponding output of the prototype NLITDB. The questions are chosen to demonstrate that the NLITDB behaves according to the specifications of the previous chapters. The questions are *not* intended to be (and are probably not) a representative sample of questions that a real user might want to submit in the airport domain (see comments about Wizard of Oz experiments in section 8.2 below). The user submits questions using the `nli` Prolog predicate:

```
| ?- nli([which,flight,left,sector3,at,pm5_00,yesterday]).
```

The system parses the question and reports the generated HPSG sign.

HPSG Sign:

```
(phrase,
  qstore:(ne_set_quant,
    elt:(det:exists,
      restind:(index:(_10148,
        minute_ent,
        tvar:plus),
      restr:(ne_set_psoa,
        elt:(part,
          part_var:_10148,
          partng:pm5_00),
```

```

                                elts:e_set))),
    elts:(ne_set_quant,
      elt:(det:interrog,
        restind:(index:(_10486,
          flight_ent,
          tvar:plus),
        restr:(ne_set_psoa,
          elt:(flight,
            arg1:_10486),
            elts:e_set))),
        elts:e_set))),
    synsem:(synsem,
      loc:(cat:(aspect:point,
        comps:e_list,
        head:(aux:minus,
          inv:minus,
          mod:none,
          prd:minus,
          vform:fin),
        spr:e_list,
        subj:e_list),
      cont:(at_op,
        main_psoa:(at_op,
          main_psoa:(past,
            et_handle:(temp_ent,
              tvar:plus),
            main_psoa:(leave_something,
              arg1:_10486,
              arg2:sector3)),
          time_spec:_10148),
          time_spec:yesterday)),
      nonloc:(inherited:slash:e_set,
        to_bind:slash:e_set)))

```

The sign above is written in ALE's notation. The sign is of sort *phrase* (it corresponds to a phrase rather than a single word), and it has the features QSTORE and SYNSEM. The QSTORE value represents a non-empty set of quantifiers (*ne_set_quant*). Its ELT feature describes the first element of that set, which is an existential quantifier. The quantifier ranges over a TOP variable, represented by an HPSG index of sort *minute_ent* (see figure 4.4 on page 126) whose TVAR is + (the index represents a TOP variable rather than a constant). The ELT value represents the TOP-like expression $\exists x2^v \text{ Part}[pm5_00^g, x2^v]$. The Prolog variable `_10148` is a pointer to the index of the quantifier, i.e. it plays the same role as the boxed numbers (e.g. $\boxed{1}$, $\boxed{2}$) in the HPSG formalism of chapter 4. The ELTS value describes the rest of the set of quantifiers, using in turn an ELT feature (second element of the overall set), and an ELTS feature (remainder of the set, in this case the empty set). The second element of the overall set

represents the TOP expression $?x1^v \text{flight}(x1^v)$. In the airport application, the lexical entries of non-predicative nouns do not introduce *Ntense* operators (this generates appropriate readings in most cases; see the discussion in section 4.9.1). This is why no *Ntense* operator is present in the second quantifier of the sign. (The effect of *Ntenses* can still be seen in the airport application in the case of non-predicative adjectives, that do introduce *Ntenses*.)

The features of the SYNSEM value are as in chapter 4. The CONT value represents the TOP expression $At[yesterday, At[x2^v, Past[x3^v, leave_something(x1^v, sector3)]]]$. The extractor of section 6.4 extracts a TOP formula from the sign, and prints it as a Prolog term.

TOP formula extracted from HPSG sign:

```
interrog(x1^v,
        and(part(pm5_00^g, x2^v),
            and(flight(x1^v),
                at(yesterday,
                    at(x2^v,
                        past(x3^v,
                            leave_something(x1^v, sector3)))))))
```

The Prolog term above stands for:

$$?x1^v \text{Part}[pm5_00^g, x2^v] \wedge \text{flight}(x1^v) \wedge \\ At[yesterday, At[x2^v, Past[x3^v, leave_something(x1^v, sector3)]]]$$

The extracted formula then goes through the post-processor of section 6.4. The post-processor eliminates the *Part* operator, adding the $pm5_00^g$ as an extra argument to the corresponding *At* operator:

TOP formula after post-processing:

```
interrog(x1^v,
        and(flight(x1^v),
            at(yesterday,
                at(pm5_00^g, x2^v,
                    past(x3^v,
                        leave_something(x1^v, sector3))))))
```

The Prolog term above stands for:

$$(6.22) \quad ?x1^v \text{flight}(x1^v) \wedge At[yesterday, \\ At[pm5_00^g, x2^v, Past[x3^v, leave_something(x1^v, sector3)]]]$$

The post-processed formula is then translated into TSQL2:

TSQL2 query:

```
(SELECT DISTINCT SNAPSHOT t8.1
FROM (SELECT DISTINCT t6.1, t7.1, t7.2, t7.3, t7.4
      VALID VALID(t6)
      FROM (SELECT DISTINCT t1.1
            VALID VALID(t1)
            FROM (SELECT DISTINCT f1.1
                  VALID VALID(f1)
                  FROM flights(PERIOD) AS f1
                  )(SUBPERIOD) AS t1
            WHERE PERIOD(TIMESTAMP 'beginning', TIMESTAMP 'forever')
            CONTAINS VALID(t1)
            ) AS t6,
      (SELECT DISTINCT t2.1, t5.1, t5.2, t5.3
        VALID VALID(t5)
        FROM (SELECT DISTINCT SNAPSHOT VALID(cp2)
              FROM gregorian AS cp2
              WHERE cp2.5 = '17' AND cp2.6 = '00'
              ) AS t2,
      (SELECT DISTINCT VALID(t4), t4.1, t4.2
        VALID VALID(t4)
        FROM (SELECT DISTINCT t3.1, t3.2
              VALID VALID(t3)
              FROM (SELECT DISTINCT flocs.1, flocs.2
                    VALID PERIOD(END(VALID(flocs)),
                                  END(VALID(flocs)))
                    FROM flight_locations(PERIOD) AS flocs
                    )(SUBPERIOD) AS t3
              WHERE t3.2 = 'sector3'
              AND INTERSECT(
                INTERSECT(t2.1,
                  INTERSECT(
                    PERIOD(TIMESTAMP 'beginning',
                          TIMESTAMP 'forever'),
                    PERIOD 'today' - INTERVAL '1' DAY)),
                PERIOD(TIMESTAMP 'beginning',
                  TIMESTAMP 'now' -
                    INTERVAL '1' MINUTE))
              CONTAINS VALID(t3)
              ) AS t4
        ) AS t5
      ) AS t7
      WHERE t6.1 = t7.3
      AND VALID(t6) = VALID(t7)
    ) AS t8
  )
```

The “SELECT DISTINCT f1.1 ... FROM flights(PERIOD) AS f1” that starts at the sixth line of the TSQL2 code is the SELECT statement to which h'_{pfun} maps predicates of the

form $flight(\tau_1)$. This statement returns a relation that shows the flights that existed at each time. The embedded `SELECT` statement that is associated with the correlation name `t6` is the result of applying the translation rule for predicates (section 5.11) to the $flight(x1^v)$ of (6.22). The “WHERE PERIOD(TIMESTAMP 'beginning', TIMESTAMP 'forever') CONTAINS VALID(t1)” corresponds to the restriction that et must fall within lt . (At this point, no constraint has been imposed on lt , and hence lt covers the whole time-axis.) This `WHERE` clause has no effect and could be removed during an optimisation phase (section 5.12).

The “SELECT DISTINCT flocs.1... flight_locations(PERIOD) AS flocs” that starts at the 23rd line of the TSQL2 code is the `SELECT` statement to which h'_{pfuns} maps predicates of the form $leave_something(\tau_1, \tau_2)$. This statement generates a relation that for each flight and location, shows the end-points of maximal periods where the flight was at that location. The embedded `SELECT` statement that is associated with `t4` is the result of applying the translation rule for predicates to the $leave_something(x1^v, sector3)$ of (6.22). `VALID(t3)` is the leaving-time, which has to fall within lt . The three nested `INTERSECTS` represent constraints that have been imposed on lt : the *Past* operator requires lt to be a subperiod of $[p_{first}, st)$ (i.e. a subperiod of `TIMESTAMP 'beginning', TIMESTAMP 'now' - INTERVAL '1' MINUTE`), the $At[pm5_00^g, \dots]$ requires lt to be a subperiod of a 5:00pm-period (`t2.1` ranges over 5:00pm-periods), and the $At[yesterday, \dots]$ requires the localisation time to be a subperiod of the previous day (`PERIOD 'today' - INTERVAL '1' DAY`).

The `SELECT` statement that is associated with `t5` is generated by the translation rule for *Past* (section 5.11), and the `SELECT` statement that is associated with `t7` is introduced by the translation rule for $At[\sigma_g, \beta, \phi']$ (section A.3.15). (The $At[yesterday, \dots]$ of (6.22) does not introduce its own `SELECT` statement, it only restricts lt ; see the translation rule for $At[\kappa, \phi']$ in section 5.11.) The `SELECT` statement that is associated with `t8` is introduced by the translation rule for conjunction (section A.3.3). It requires the attribute values that correspond to the $x1^v$ arguments of $flight(x1^v)$ and $leave_something(x1^v, sector3)$, and the event times where the two predicates are true to be identical. Finally, the top-level `SELECT` statement is introduced by the translation rule for $? \beta_1 ? \beta_2 ? \beta_3 \dots ? \beta_k \phi'$ (section A.4.1). It returns a snapshot relation that contains the attribute values that correspond to $x1^v$ (the flights).

No further comments need to be made about the generated HPSG signs and TSQL2 queries. To save space, I do not show these in the rest of the examples. I also do not show the TOP formulae before the post-processing, unless some point needs to be made about them.

As noted in section 2.5.3, no attempt is made to block progressive forms of state verbs. The progressive forms of these verbs are taken to have the same meanings as the corresponding non-progressive ones. This causes the two questions below to receive the same TOP formula.

```
| ?- nli([which,tanks,contain,water]).
```

TOP formula after post-processing:

```
interrog(x1^v,
         and(tank(x1^v),
            pres(contains(x1^v, water))))
```

```
| ?- nli([which,tanks,are,containing,water]).
```

TOP formula after post-processing:

[same formula as above]

There are two lexical entries for the base form of “to service”, one for the habitual homonym, and one for the non-habitual one. The habitual entry introduces the predicate functor *hab_servicer_of* and classifies the base form as state. The non-habitual entry introduces the functor *actl_servicing* and classifies the base form as culminating activity. The simple present lexical rule (section 4.7.1) generates a simple present lexical entry for only the habitual homonym (whose base form is state). Hence, the “services” below is treated as the simple present of the habitual homonym (not as the simple present of the non-habitual homonym), and only a formula that contains the *hab_servicer_of* functor is generated. This captures the fact that the question can only have a habitual meaning (it cannot refer to a servicer that is actually servicing BA737 at the present; the reader is reminded that the scheduled-to-happen reading of the simple present is ignored in this thesis – see section 2.5.1).

```
| ?- nli([which,servicer,services,ba737]).
```

TOP formula after post-processing:

```
interrog(x1^v,
```

```
and(servicer(x1^v),
    pres(hab_servicer_of(x1^v, ba737))))
```

In contrast, the present participle lexical rule (section 4.7.1) generates progressive entries for both the non-habitual (culminating activity base form) and the habitual (state base form) homonyms. This causes the question below to receive two parses, one where the “*is servicing*” is the present continuous of the non-habitual homonym, and one where it is the present continuous of the habitual homonym. This gives rise to two formulae, one involving the *actl_servicing* functor (the servicer must be servicing BA737 at the present), and one involving the *hab_servicer_of* functor (the servicer must be the current normal servicer of BA737). (The $x2^v$ in the first formula is an occurrence identifier; see section 3.16.) The habitual reading of the second formula seems rather unlikely in this case.

```
| ?- nli([which,servicer,is,servicing,ba737]).
```

TOP formula after post-processing:

```
interrog(x1^v,
    and(servicer(x1^v),
        pres(actl_servicing(x2^v, x1^v, ba737))))
```

TOP formula after post-processing:

```
interrog(x1^v,
    and(servicer(x1^v),
        pres(hab_servicer_of(x1^v, ba737))))
```

There are also different lexical entries for the actual “*to depart*” and the habitual “*to depart*” (at some time). The habitual entry introduces the functor *hab_dep_time*, requires an “*at ...*” complement, and classifies the base form as state. The non-habitual entry introduces the functor *actl_depart*, requires no complement, and classifies the base form as point. When “*BA737 departed at 5:00pm.*” is taken to involve the habitual homonym, “*at 5:00pm*” is treated as the complement that specifies the habitual departure time (the second argument of *hab_dep_time*(τ_1, τ_2)). When the sentence is taken to involve the non-habitual homonym, “*at 5:00pm*” is treated as a temporal modifier, and it introduces an *At* operator (section 4.11.1). In the following question, this analysis leads to two formulae: one where each reported flight must have actually departed at 5:00pm at least once in 1993, and one where the habitual departure time of each reported flight must have been 5:00pm some time in 1993. The second reading

seems the preferred one in this example.

```
| ?- nli([which,flights,departed,at,pm5_00,in,y1993]).
```

TOP formula after post-processing:

```
interrog(x1^v,
        and(flight(x1^v),
            at(y1993,
                at(pm5_00^g, x2^v,
                    past(x3^v,
                        act1_depart(x1^v))))))
```

TOP formula after post-processing:

```
interrog(x1^v,
        and(flight(x1^v),
            at(y1993,
                past(x2^v,
                    hab_dep_time(x1^v, pm5_00))))))
```

The first question below receives no parse, because “to circle” is classified as activity verb (there is no habitual state homonym in this case), and the simple present lexical rule does not generate simple present lexical entries for activity verbs. In contrast, the present participle lexical rule does generate progressive entries for activity verbs. This causes the second question below to be mapped to the formula one would expect. The failure to parse the first question is justified, in the sense that the question seems to be asking about flights that have some circling habit, and the NLITDB has no access to information on circling habits. A more cooperative response, however, is needed to explain this to the user.

```
| ?- nli([does,ba737,circle]).
```

```
  **No (more) parses.
```

```
| ?- nli([is,ba737,circling]).
```

TOP formula after post-processing:

```
pres(circling(ba737))
```

Following the arrangements of section 4.11.2, in the following question where a culminating activity combines with a period adverbial, two formulae are generated: one where the inspection must have simply been completed on 1/5/92, and one where the whole inspection (from start to completion) must have been carried out on 1/5/92.

The first reading seems unlikely in this example, though as discussed in section 2.9.2, there are sentences where the first reading is the intended one.

```
| ?- nli([who,inspected,uk160,on,d1_5_92]).
```

TOP formula after post-processing:

```
interrog(x1^v,
        at(d1_5_92,
            end(past(x2^v,
                    culm(inspecting(x3^v, x1^v, uk160))))))
```

TOP formula after post-processing:

```
interrog(x1^v,
        at(d1_5_92,
            past(x2^v,
                culm(inspecting(x3^v, x1^v, uk160))))))
```

In the following question, the punctual adverbial “at 5:00pm” combines with a culminating activity. According to section 2.9.1, two readings arise: one where the taxiing starts at 5:00pm, and one where it finishes at 5:00pm. In both cases, the punctual adverbial causes the aspect of “*which flight taxied to gate 2 at 5:00pm*” to become point. That point sentence then combines with the period adverbial “*yesterday*”. According to section 2.9.2, the instantaneous situation of the point phrase (the start or end of the taxiing) must occur within the period of the adverbial. This analysis leads to two formulae: one where the taxiing starts at 5:00pm on the previous day, and one where the taxiing finishes at 5:00pm on the previous day. These formulae capture the most likely readings of the question. Unfortunately, if the order of “at 5:00pm” and “*yesterday*” is reversed, the generated formulae are not equivalent to the ones below (see the discussion in section 4.16)

```
| ?- nli([which,flight,taxied,to,gate2,at,pm5_00,yesterday]).
```

TOP formula after post-processing:

```
interrog(x1^v,
        and(flight(x1^v),
            at(yesterday,
                at(pm5_00^g, x2^v,
                    end(past(x3^v,
                        culm(taxiing_to(x4^v, x1^v, gate2))))))))
```

TOP formula after post-processing:

```
interrog(x1^v,
        and(flight(x1^v),
            at(yesterday,
                at(pm5_00^g, x2^v,
                    begin(past(x3^v,
                        culm(taxiing_to(x4^v, x1^v, gate2))))))))))
```

In the sentence below (which is treated as a yes/no question), the treatment of past perfects and punctual adverbials of section 4.11.1 allows “at 5:00pm” to modify either the verb phrase “left gate 2”, or the entire “BA737 had left gate 2”. This gives rise to two TOP formulae: one where 5:00pm is the time at which BA737 left gate 2, and one where 5:00pm is a reference time at which BA737 had already left gate 2. The two formulae capture the two most likely readings of the sentence.

| ?- nli([ba737,had,left,gate2,at,pm5_00]).

TOP formula after post-processing:

```
past(x2^v,
    perf(x3^v,
        at(pm5_00^g, x1^v,
            leave_something(ba737, gate2))))
```

TOP formula after post-processing:

```
at(pm5_00^g, x1^v,
    past(x2^v,
        perf(x3^v,
            leave_something(ba737, gate2))))
```

Similarly, in the following question, the “at 5:00pm” is allowed to modify either the verb phrase “taken off”, or the entire “BA737 had taken off”. In the first case, the verb phrase still has the aspectual class of the base form, i.e. culminating activity. According to section 2.9.1, 5:00pm is the time where the taking off was completed or started. These two readings are captured by the first and second formulae below. (The second reading seems unlikely in this example.) In the case where “at 5:00pm” modifies the entire “BA737 had taken off”, the “had” has already caused the aspect of “BA737 had taken off” to become (consequent) state. According to section 2.9.1, in that case 5:00pm is simply a time-point where the situation of the sentence (having departed) holds. This reading is captured by the third formula.

| ?- nli([ba737,had,taken,off,at,pm5_00]).

TOP formula after post-processing:

```
past(x2^v,
    perf(x3^v,
        at(pm5_00^g, x1^v,
            end(culm(taking_off(x4^v, ba737))))))
```

TOP formula after post-processing:

```
past(x2^v,
    perf(x3^v,
        at(pm5_00^g, x1^v,
            begin(culm(taking_off(x4^v, ba737))))))
```

TOP formula after post-processing:

```
at(pm5_00^g, x1^v,
    past(x2^v,
        perf(x3^v,
            culm(taking_off(x4^v, ba737))))))
```

The first question below receives the formula one would expect. As discussed in section 4.16, in the second question below the grammar of chapter 4 allows two parses: one where “yesterday” attaches to “BA737 was circling”, and one where “yesterday” attaches to “BA737 was circling for two hours”. These two parses give rise to two different but logically equivalent formulae.

```
| ?- nli([ba737,was,circling,for,two,hours,yesterday]).
```

TOP formula after post-processing:

```
at(yesterday,
    for(hour^c, 2,
        past(x1^v,
            circling(ba737))))
```

```
| ?- nli([yesterday,ba737,was,circling,for,two,hours]).
```

TOP formula after post-processing:

```
for(hour^c, 2,
    at(yesterday,
        past(x1^v,
            circling(ba737))))
```

TOP formula after post-processing:

```
at(yesterday,
    for(hour^c, 2,
```

```
past(x1^v,
      circling(ba737)))
```

The following example reveals a problem in the current treatment of temporal modifiers. The HPSG version of this thesis (section 4.11) allows temporal modifiers to attach only to finite sentences (finite verb forms that have already combined with their subjects and complements) or past participle verb phrases (past participles that have combined with all their complements but not their subjects). In both cases, the temporal modifier attaches after the verb has combined with all its complements. English temporal modifiers typically appear either at the beginning or the end of the sentence (not between the verb and its complements), and hence requiring temporal modifiers to attach after the verb has combined with its complements is in most cases not a problem. However, in the following question (which most native English speakers find acceptable) the temporal modifier (“*for two hours*”) is between the verb (“*queued*”) and its complement (“*for runway2*”). Therefore, the temporal modifier cannot attach to the verb after the verb has combined with its complement, and the system fails to parse the sentence. (In contrast, “*UK160 queued for runway 2 for two hours.*”, where the temporal modifier follows the complement, is parsed without problems.)

```
| ?- nli([uk160,queued,for,two,hours,for,runway2]).
```

```
**No (more) parses.
```

As explained in section 4.17, the post-processing removes *Culm* operators that are within *For* operators introduced by “for ... ” adverbials. This is demonstrated in the following example. The “for ... ” adverbial introduces a `for_remove_culm` pseudo-operator, which can be thought of as a *For* operator with a flag attached to it, that signals that *Culms* within the *For* operator must be removed. The post-processor removes the *Culm*, and replaces the `for_remove_culm` with an ordinary *For* operator.

```
| ?- nli([which,flight,boarded,for,two,hours]).
```

TOP formula extracted from HPSG sign:

[illegible]

TOP formula after post-processing:

```
interrog(x1^v,
        and(flight(x1^v),
            for(hour^c, 2,
                past(x2^v,
                    boarding(x3^v, x1^v))))))
```

Duration “in ... ” adverbials introduce *For* operators that carry no flag to remove enclosed *Culms*. In the following question, this leads to a formula that (correctly) requires the boarding to have been completed.

```
| ?- nli([which,flight,boarded,in,two,hours]).
```

TOP formula after post-processing:

```
interrog(x1^v,
        and(flight(x1^v),
            for(hour^c, 2,
                past(x2^v,
                    culm(boarding(x3^v, x1^v))))))
```

As explained in section 2.5.4, the present perfect is treated in exactly the same way as the simple past. This causes the two questions below to receive the same formula.

```
| ?- nli([which,flight,has,been,at,gate2,for,two,hours]).
```

TOP formula after post-processing:

```
interrog(x1^v,
        and(flight(x1^v),
            for(hour^c, 2,
                past(x2^v,
                    located_at(x1^v, gate2))))))
```

```
| ?- nli([which,flight,was,at,gate2,for,two,hours]).
```

TOP formula after post-processing:

[same formula as above]

As discussed in section 2.6, when “*finished*” combines with a culminating activity, the situation must have reached its completion. In contrast, when “*stopped*” combines with a culminating activity, the situation must have simply stopped, without necessarily reaching its completion. This difference is captured in the two formulae below by the existence or absence of a *Culm*.


```
| ?- nli([j_adams,finished,inspecting,uk160,at,pm5_00]).
```

TOP formula after post-processing:

```
at(pm5_00^g, x1^v,
   past(x2^v,
        end(culm(inspecting(x3^v, j_adams, uk160))))))
```

```
| ?- nli([j_adams,stopped,inspecting,uk160,at,pm5_00]).
```

TOP formula after post-processing:

```
at(pm5_00^g, x1^v,
   past(x2^v,
        end(inspecting(x3^v, j_adams, uk160))))
```

In the airport domain, non-predicative adjectives (like “closed” below) introduce *Ntense* operators. In the question below, the formula that is extracted from the HPSG sign contains an *Ntense* whose first argument is a variable. As explained in section 4.17, this leads to two different formulae after the post-processing, one where “closed” refers to the present, and one where “closed” refers to the time of the verb tense.

```
| ?- nli([was,any,flight,on,a,closed,runway,yesterday]).
```

TOP formula extracted from HPSG sign:

```
and(flight(x1^v),
    and(and(ntense(x2^v, closed(x3^v)),
            runway(x3^v)),
        at(yesterday,
            past(x4^v,
                located_at(x1^v, x3^v))))))
```

****Post processing of TOP formula generated 2 different formulae.**

TOP formula after post-processing:

```
and(flight(x1^v),
    and(and(ntense(now, closed(x3^v)),
            runway(x3^v)),
        at(yesterday,
            past(x4^v,
                located_at(x1^v, x3^v))))))
```

TOP formula after post-processing:

```
and(flight(x1^v),
    and(and(ntense(x4^v, closed(x3^v)),
            runway(x3^v)),
        at(yesterday,
```

```
past(x4^v,
      located_at(x1^v, x3^v))))))
```

In the following question, the “currently” clarifies that “closed” refers to the present. The *Ntense* in the formula extracted from the HPSG sign has *now** as its first argument. The post-processing has no effect.

```
| ?- nli([was,any,flight,on,a,currently,closed,runway,yesterday]).
```

TOP formula extracted from HPSG sign:

```
and(flight(x1^v),
     and(and(ntense(now, closed(x2^v)),
               runway(x2^v)),
         at(yesterday,
            past(x3^v,
                 located_at(x1^v, x2^v))))))
```

In the following question, the verb tense refers to the present, and hence “closed” can only refer to a currently closed runway. The post-processor generates only one formula, where the first argument of *Ntense* is *now**.

```
| ?- nli([is,any,flight,on,a,closed,runway]).
```

TOP formula extracted from HPSG sign:

```
and(flight(x1^v),
     and(and(ntense(x2^v, closed(x3^v)),
               runway(x3^v)),
         pres(located_at(x1^v, x3^v))))
```

TOP formula after post-processing:

```
and(flight(x1^v),
     and(and(ntense(now, closed(x3^v)),
               runway(x3^v)),
         pres(located_at(x1^v, x3^v))))
```

Predicative adjectives do not introduce *Ntenses* (section 4.10), and TOP predicates introduced by these adjectives always end up within the operator(s) of the verb tense. This captures the fact that predicative adjectives always refer to the time of the verb tense.

```
| ?- nli([was,gate2,open,on,monday]).
```

TOP formula after post-processing:

```
at(monday^g, x1^v
   past(x2^v,
        open(gate2)))
```

For reasons explained in section 4.9.2, the system fails to parse sentences that contain proper names or names of days, months, etc. when these are used as predicative noun phrases (e.g. the first two questions below). Other predicative noun phrases pose no problem (e.g. the third question below).

```
| ?- nli([d1_1_91,was,a,monday]).
```

```
    **No (more) parses.
```

```
| ?- nli([ba737,is,uk160]).
```

```
    **No (more) parses.
```

```
| ?- nli([ba737,is,a,flight]).
```

TOP formula after post-processing:

```
pres(flight(ba737))
```

Multiple interrogative words can be handled, as demonstrated below.

```
| ?- nli([which,flight,is,at,which,gate]).
```

TOP formula after post-processing:

```
interrog(x1^v,
         interrog(x2^v,
                 and(gate(x1^v),
                     and(flight(x2^v),
                         pres(located_at(x2^v, x1^v))))))
```

In the first question below, the grammar of chapter 4 allows “yesterday” to attach to either “BA737 was circling” or to the whole “did any flight leave a gate while BA737 was circling”. Two HPSG signs are generated as a result of this, from which two different but logically equivalent formulae are extracted. In contrast, in the second question below, the “yesterday” cannot attach to “BA737 was circling”, because of the intervening “while” (“while BA737 was circling” is treated as an adverbial, and “yesterday” cannot attach to another adverbial). Consequently, only one formula is generated.

| ?- nli([did,any,flight,leave,a,gate,while,ba737,was,circling,yesterday]).

TOP formula after post-processing:

```
and(flight(x1^v),
    and(gate(x2^v),
        at(at(yesterday,
            past(x3^v,
                circling(ba737))),
            past(x4^v,
                leave_something(x1^v, x2^v))))))
```

TOP formula after post-processing:

```
and(flight(x1^v),
    and(gate(x2^v),
        at(yesterday,
            at(past(x3^v,
                circling(ba737)),
                past(x4^v,
                    leave_something(x1^v, x2^v))))))
```

| ?- nli([did,any,flight,leave,a,gate,yesterday,while,ba737,was,circling]).

TOP formula after post-processing:

```
and(flight(x1^v),
    and(gate(x2^v),
        at(past(x3^v,
            circling(ba737)),
            at(yesterday,
                past(x5^v,
                    leave_something(x1^v, x2^v))))))
```

In the questions below, the subordinate clause is a (progressive) state. According to section 2.10.2, in the first question the flights must have arrived before a time-point where BA737 started to board (“to arrive” is a point verb in the airport domain). In the second question, section 2.10.2 allows two readings: the flights must have arrived after a time-point where BA737 started or stopped boarding. The generated formulae capture these readings.

| ?- nli([which,flights,arrived,before,ba737,was,boarding]).

TOP formula after post-processing:

```
interrog(x1^v,
    and(flight(x1^v),
        before(past(x2^v,
            boarding(x3^v, ba737)),
            past(x4^v,
```

```
actl_arrive(x1^v))))
```

```
| ?- nli([which,flights,arrived,after,ba737,was,boarding])).
```

TOP formula after post-processing:

```
interrog(x1^v,
  and(flight(x1^v),
    after(begin(past(x2^v,
      boarding(x3^v, ba737))),
      past(x4^v,
        actl_arrive(x1^v))))))
```

TOP formula after post-processing:

```
interrog(x1^v,
  and(flight(x1^v),
    after(past(x2^v,
      boarding(x3^v, ba737))),
      past(x4^v,
        actl_arrive(x1^v))))))
```

Below, the subordinate clause is a culminating activity. In the first question, according to section 2.10.2 the flights must have arrived before a time-point where BA737 finished or started to board. In the second question, the flights must have arrived after a time-point where BA737 finished boarding. These readings are captured by the generated formulae.

```
| ?- nli([which,flights,arrived,before,ba737,boarded])).
```

TOP formula after post-processing:

```
interrog(x1^v,
  and(flight(x1^v),
    before(end(past(x2^v,
      culm(boarding(x3^v, ba737))))),
      past(x4^v,
        actl_arrive(x1^v))))))
```

TOP formula after post-processing:

```
interrog(x1^v,
  and(flight(x1^v),
    before(past(x2^v,
      culm(boarding(x3^v, ba737))),
      past(x4^v,
        actl_arrive(x1^v))))))
```

```
| ?- nli([which,flights,arrived,after,ba737,boarded])).
```

TOP formula after post-processing:

```
interrog(x1^v,
        and(flight(x1^v),
            after(past(x2^v,
                    culm(boarding(x3^v, ba737))),
                past(x4^v,
                    actl_arrive(x1^v))))))
```

In the next two questions, the subordinate clause is a consequent state. According to section 2.10.2, in the first question the flights must have arrived before the situation of the subordinate clause (having boarded) began, i.e. before BA737 finished boarding. In the second question, the flights must have arrived after the situation of the subordinate clause (having boarded) began, i.e. after BA737 finished boarding. These readings are captured by the generated TOP formulae.

| ?- nli([which,flights,arrived,before,ba737,had,boarded]).

TOP formula after post-processing:

```
interrog(x1^v,
        and(flight(x1^v),
            before(past(x2^v,
                    perf(x3^v,
                        culm(boarding(x4^v,
                                    ba737)))))
                past(x5^v,
                    actl_arrive(x1^v))))))
```

| ?- nli([which,flights,arrived,after,ba737,had,boarded]).

TOP formula after post-processing:

```
interrog(x1^v,
        and(flight(x1^v),
            after(begin(past(x2^v,
                    perf(x3^v,
                        culm(boarding(x4^v,
                                    ba737)))))
                past(x5^v,
                    actl_arrive(x1^v))))))
```

The question below combines a “when” interrogative and a “while ... ” clause. The generated formula asks for maximal past circling-periods of BA737 that fall within

maximal past periods where UK160 was located at gate 2.

```
| ?- nli([when,while,uk160,was,at,gate2,was,ba737,circling]).
```

TOP formula after post-processing:

```
interrog_mxl(x3^v,
             at(past(x2^v,
                    located_at(uk160, gate2)),
             past(x3^v,
                 circling(ba737))))
```

Finally, the question below receives two formulae: the first one asks for times of past actual departures; the second one asks for past normal departure times. (The latter reading is easier to accept if an adverbial like “in 1992” is attached.) In the second question, only a formula for the habitual reading is generated, because the simple present lexical rule (section 4.7.1) does not generate a simple present lexical entry for the non-habitual “to depart” (which is a point verb).

```
| ?- nli([when,did,ba737,depart]).
```

TOP formula after post-processing:

```
interrog_mxl(x2^v,
             past(x2^v,
                 act1_depart(ba737)))
```

TOP formula after post-processing:

```
interrog(x1^v,
        past(x2^v,
            hab_dep_time(ba737, x1^v)))
```

```
| ?- nli([when,does,ba737,depart]).
```

TOP formula after post-processing:

```
interrog(x1^v,
        pres(hab_dep_time(ba737, x1^v)))
```

6.9 Speed issues

As already noted, the prototype NLITDB was developed simply to demonstrate that the mappings from English to TOP and from TOP to TSQL2 are implementable. Execution speed was not a priority, and the NLITDB code is by no means optimised for fast

execution. On a lightly loaded Sun SPARCstation 5, single-clause questions with single parses are typically mapped to TSQL2 queries in about 15–30 seconds. Longer questions with subordinate clauses and multiple parses usually take 1–2 minutes to process. (These times include the printing of all the HPSG signs, TOP formulae, and TSQL2 queries.) The system’s speed seems acceptable for a research prototype, but it is unsatisfactory for real-life applications.

Whenever a modification is made in the software, the code of the affected modules has to be recompiled. This takes only a few seconds in the case of modules that are written in Prolog (the post-processor and the TOP to TSQL2 translator), but it is very time-consuming in the case of modules that are written in ALE’s formalism (the components of the HPSG grammar and the extractor of TOP formulae). This becomes particularly annoying when experimenting with the grammar, as in many cases after modifying the grammar all its components (sort hierarchy, lexical rules, etc.) have to be recompiled, and this recompilation takes approximately 8 minutes on the above machine.

6.10 Summary

The framework of this thesis was tested by developing a prototype NLITDB, implemented using Prolog and ALE. The prototype was configured for the hypothetical airport application. A number of sample questions were used to demonstrate that the system behaves according to the specifications of the previous chapters. The architecture of the prototype is currently minimal. A preprocessor, mechanisms for quantifier-scoping and anaphora resolution, an equivalential translator, a response generator, and configuration tools would have to be added if the system were to be used in real-life applications. Execution speed would also have to be improved.

Chapter 7

Comparison with Previous Work on NLITDBs

“Other times other manners.”

This chapter begins with a discussion of previous work on NLITDBs. The discussion identifies six problems from which previous proposals on NLITDBs suffer. I then examine if the framework of this thesis overcomes these problems.

7.1 Previous work on NLITDBs

This section discusses previous work on NLITDBs. Clifford’s work, which is the most significant and directly relevant to this thesis, is presented first.

7.1.1 Clifford

Clifford [Clifford 90] defined a temporal version of the relational model. He also showed how a fragment of English questions involving time can be mapped systematically to logical expressions whose semantics are defined in terms of a database structured according to his model.¹ Clifford’s approach is notable in that both the semantics of the English fragment and of the temporal database are defined within a common model-theoretic framework, based on Montague semantics [Dowty *et al.* 81].

¹ Parts of [Clifford 90] can be found in [Clifford 87a], [Clifford 87b], and [Clifford 88]. The database model of this section is that of [Clifford 90]. A previous version of this model appears in [Clifford & Warren 83].

Clifford extended the syntactic coverage of Montague’s PTQ grammar, to allow past, present, and future verb forms, some temporal connectives and adverbials (e.g. “while”, “during”, “in 1978”, “yesterday”), and questions. (7.1) – (7.5) are all within Clifford’s syntactic coverage. (Assertions like (7.3) are treated as yes/no questions.)

- (7.1) Is it the case that Peter earned 25K in 1978?
- (7.2) Does Rachel manage an employee such that he earned 30K?
- (7.3) John worked before Mary worked.
- (7.4) Who manages which employees?
- (7.5) When did Liz manage Peter?

Clifford does not allow progressive verb forms. He also claims that no distinction between progressive and non-progressive forms is necessary in the context of NLITDBS (see p.12 of [Clifford 87a]). According to Clifford’s view, (7.6) can be treated in exactly the same manner as (7.7). This ignores the fact that (7.7) most probably refers to a company that habitually or normally services BA737, or to a company that will service BA737 according to some plan, not to a company that is actually servicing BA737 at the present. In contrast, (7.6) most probably refers to a company that is actually servicing BA737 at the present, or to a company that is going to service BA737. Therefore, the NLITDB should not treat the two questions as identical, if its responses are to be appropriate to the meanings users have in mind.

- (7.6) Which company is servicing flight BA737?
- (7.7) Which company services flight BA737?

Clifford also does not discuss perfect tenses (present perfect, past perfect, etc.), which do not seem to be allowed in his framework. Finally, he employs no aspectual taxonomy (this will be discussed in section 7.2.1).

Following the Montague tradition, Clifford employs an intensional higher order language (called IL_s) to represent the meanings of English questions. There is a set of syntactic rules that determine the syntactic structure of each sentence, and a set of semantic rules that map syntactic structures to expressions of IL_s . For example, (7.5) is mapped to the IL_s expression of (7.8).

- (7.8) $\lambda i_1[[i_1 < i] \wedge \exists y[EMP'_*(i_1)(Peter) \wedge$
 $MGR'(i_1)(y) \wedge y(i_1) = Liz \wedge AS\bot(Peter, y)]]$

Roughly speaking, (7.8) has the following meaning. $EMP'_*(i_1)(Peter)$ means that Peter must be an employee at the time-point i_1 . $MGR'(i_1)(y)$ means that y must be a partial function from time-points to managers (an *intension* in Montague semantics terminology) which is defined for (at least) the time-point i_1 . $AS.1(Peter, y)$ requires y to represent the history of Peter's managers (i.e. the value $y(i_1)$ of y at each time-point i_1 must be the manager of Peter at that time-point). The $y(i_1) = Liz$ requires the manager of Peter at i_1 to be Liz. Finally, i is the present time-point, and $i_1 < i$ means that i_1 must precede i . (7.8) requires all time-points i_1 to be reported, such that i_1 precedes the present time-point, Peter is an employee at i_1 , and Peter's manager at i_1 is Liz.

The following (from [Clifford 90]) is a relation in Clifford's database model (called HRDM – Historical Relational Database Model).

<i>emprel</i>				
<i>EMP</i>	<i>MGR</i>	<i>DEPT</i>	<i>SAL</i>	<i>lifespan</i>
<i>Peter</i>	$\begin{bmatrix} S2 \rightarrow Elsie \\ S3 \rightarrow Liz \end{bmatrix}$	$\begin{bmatrix} S2 \rightarrow Hardware \\ S3 \rightarrow Linen \end{bmatrix}$	$\begin{bmatrix} S2 \rightarrow 30K \\ S3 \rightarrow 35K \end{bmatrix}$	$\{S2, S3\}$
<i>Liz</i>	$\begin{bmatrix} S2 \rightarrow Elsie \\ S3 \rightarrow Liz \end{bmatrix}$	$\begin{bmatrix} S2 \rightarrow Toy \\ S3 \rightarrow Hardware \end{bmatrix}$	$\begin{bmatrix} S2 \rightarrow 35K \\ S3 \rightarrow 50K \end{bmatrix}$	$\{S2, S3\}$
<i>Elsie</i>	$\begin{bmatrix} S1 \rightarrow Elsie \\ S2 \rightarrow Elsie \end{bmatrix}$	$\begin{bmatrix} S1 \rightarrow Toy \\ S2 \rightarrow Toy \end{bmatrix}$	$\begin{bmatrix} S1 \rightarrow 50K \\ S2 \rightarrow 50K \end{bmatrix}$	$\{S1, S2\}$

The *lifespan* of each tuple shows the time-points (“states” in Clifford's terminology) for which the tuple carries information. In HRDM, attribute values are not necessarily atomic. They can also be sets of time-point denoting symbols (as in the case of *lifespan*), or partial functions from time-point denoting symbols to atomic values. The relation above means that at the time-point $S2$ the manager of Peter was Elsie, and that at $S3$ the manager of Peter was Liz. HRDM uses additional time-stamps to cope with schema-evolution (section 1.4). I do not discuss these here.

Clifford shows how the semantics of IL_s expressions can be defined in terms of an HRDM database (e.g. how the semantics of (7.8) can be defined in terms of information in *emprel*). He also defines an algebra for HRDM, similar to the relational algebra of the traditional relational model [Ullman 88]. (Relational algebra is a theoretical database

query language. Most DBMSs do not support it directly. DBMS users typically specify their requests in more user-friendly languages, like SQL. DBMSs, however, often use relational algebra internally, to represent operations that need to be carried out to satisfy the users' requests.) The answer to (7.5) can be found using (7.9), which is an expression in Clifford's algebra.

$$(7.9) \quad \omega(\sigma\text{-}WHEN_{EMP=Peter, MGR=Liz}(emprel))$$

$\sigma\text{-}WHEN_{EMP=Peter, MGR=Liz}(emprel)$ generates a single-tuple relation (shown below as *emprel2*) that carries the information of Peter's tuple from *emprel*, restricted to when his manager was Liz. The ω operator returns a set of time-point denoting symbols, that represents all the time-points for which there is information in the relation-argument of ω . In our example, (7.9) returns $\{S3\}$.

<i>emprel2</i>				
<i>EMP</i>	<i>MGR</i>	<i>DEPT</i>	<i>SAL</i>	<i>lifespan</i>
<i>Peter</i>	$[S3 \rightarrow Liz]$	$[S3 \rightarrow Linen]$	$[S3 \rightarrow 35K]$	$\{S3\}$

Clifford outlines an algorithm for mapping IL_s expressions to appropriate algebraic expressions (e.g. mapping (7.8) to (7.9); see p.170 of [Clifford 90]). The description of this algorithm, however, is very sketchy and informal.

According to Clifford ([Clifford 87a], p.16), a parser for his version of the PTQ grammar (that presumably also maps English questions to IL_s expressions) has been developed. Clifford, however, does not provide any information on whether or not a translator from IL_s to his algebra was ever implemented (as noted above, this mapping is not fully defined), and there is no indication that Clifford's framework was ever used to implement an actual NLITDB.

7.1.2 Bruce

Bruce's CHRONOS [Bruce 72] is probably the first natural language question-answering system that attempted to address specifically time-related issues. CHRONOS is not really an interface to a stand-alone database system. When invoked, it has no information about the world. The user "teaches" CHRONOS various facts (using statements

like (7.10) and (7.11)), which are stored internally as expressions of a Lisp-like representation language. Questions about the stored facts can then be asked (e.g. (7.12), (7.13)).

- (7.10) The American war for independence began in 1775.
- (7.11) The articles of confederation period was from 1777 to 1789.
- (7.12) Does the American war for independence coincide with the time from 1775 to 1781?
- (7.13) Did the time of the American war for independence overlap the articles of confederation period?

Bruce defines formally a model of time, and explores how relations between time-segments of that model can represent the semantics of some English temporal mechanisms (mainly verb tenses). Bruce's time-model and temporal relations seem to underlie CHRONOS' Lisp-like representation language. Bruce, however, provides no information about the representation language itself. With the exception of verb tenses, there is very little information on the linguistic coverage of the system and the linguistic assumptions on which the system is based, and scarcely any information on the mapping from English to representation language. (The discussion in [Bruce 72] suggests that the latter mapping may be based on simplistic pattern-matching techniques.) Finally, Bruce does not discuss exactly how the stored facts are used to answer questions like (7.12) and (7.13).

7.1.3 De, Pan, and Whinston

De, Pan, and Whinston [De *et al.* 85] [De *et al.* 87] describe a question-answering system that can handle a fragment of English questions involving time. The "temporal database" in this case is a rather ad hoc collection of facts and inference rules (that can be used to infer new information from the facts), rather than a principled database built on a well-defined database model. Both the grammar of the linguistic processor and the facts and rules of the database are specified in "equational logic" (a kind of logic-programming language). There is no clear intermediate representation language, and it is very difficult to distinguish the part of the system that is responsible for the linguistic processing from the part of the system that is responsible for retrieving information from the "database". De et al. consider this an advantage, but it clearly

sacrifices modularity and portability. For example, it is very hard to see which parts of the software would have to be modified if the natural language processor were to be used with a commercial DBMS.

The system of De et al. does not seem to be based on any clear linguistic analysis. There is also very little information in [De *et al.* 85] and [De *et al.* 87] on exactly which temporal linguistic mechanisms are supported, and which semantics are assigned to these mechanisms. Furthermore, no aspectual classes are used (see related comments in section 7.2.1).

7.1.4 Moens

Moens' work on temporal linguistic phenomena [Moens 87] [Moens & Steedman 88] has been highly influential in the area of tense and aspect theories (some ideas from Moens' work were mentioned in chapter 2). In the last part of [Moens 87] (see also [Moens 88]), Moens develops a simplistic NLITDB. This has a very limited linguistic coverage, and is mainly intended to illustrate Moens' tense and aspect theory, rather than to constitute a detailed exploration of issues related to NLITDBs.

As in the case of Bruce and De et al., Moens' "database" is not a stand-alone system built according to an established (e.g. relational) database model. Instead, it is a collection of Prolog facts of particular forms, that record information according to an idiosyncratic and unclearly defined database model. Apart from purely temporal information (that shows when various events took place), Moens' database model also stores information about *episodes*. According to Moens, an episode is a sequence of "contingently" related events. Moens uses the term "contingency" in a rather vague manner: in some cases it denotes a consequence relation (event A was a consequence of event B); in other cases it is used to refer to events that constitute steps towards the satisfaction of a common goal. The intention is, for example, to be able to store an event where John writes chapter 1 of his thesis together with an event where John writes chapter 2 of his thesis as constituting parts of an episode where John writes his thesis. Some episodes may be parts of larger episodes (e.g. the episode where John writes his thesis could be part of a larger episode where John earns his PhD).

Moens claims that episodic information of this kind is necessary if certain time-related linguistic mechanisms (e.g. "when ..." clauses, present perfect) are to be handled

appropriately. Although I agree that episodic information seems to play an important role in how people perceive temporal information, it is often difficult to see how Moens' episodic information (especially when events in an episode are linked with consequence relations) can be used in a practical NLITDB (e.g. in section 2.5.4, I discussed common claims that the English present perfect involves a consequence relation, and I explained why an analysis of the present perfect that posits a consequence relation is impractical in NLITDBs). By assuming that the database contains episodic information, one also moves away from current proposals in temporal databases, that do not consider information of this kind. For these reasons, I chose not to assume that the database provides episodic information. As was demonstrated in the previous chapters, even in the absence of such information reasonable responses can be generated in a large number of cases.

Moens' database model is also interesting in that it provides some support for *imprecise temporal information*. One may know, for example, that two events A and B occurred, and that B was a consequence of A, without knowing the precise times where A and B occurred. Information of this kind can be stored in Moens' database, because in his model events are not necessarily associated with times. One can store events A and B as a sequence of contingently related events (here contingency would have its consequence meaning) without assigning them specific times. (If, however, there is no contingency relation between the two events and their exact times are unknown, Moens' model does not allow the relative order of A and B to be stored.) Although there has been research on imprecise temporal information in databases (e.g. [Brusoni *et al.* 95], [Koubarakis 95]), most of the work on temporal databases assumes that events are assigned specific times. To remain compatible with this work, I adopted the same assumption.

Moens' system uses a subset of Prolog as its meaning representation language. English questions are translated into expressions of this subset using a DCG grammar [Pereira & Warren 80], and there are Prolog rules that evaluate the resulting expressions against the database. Moens provides no information about the DCG grammar. Also, the definition of the meaning representation language is unclear. It is difficult to see exactly which Prolog expressions are part of the representation language, and the semantics of the language is defined in a rather informal way (by listing Prolog code that evaluates some of the possible expressions of the representation language against

the database).

7.1.5 Spenceley

Spenceley [Spenceley 89] developed a version of the MASQUE natural language front-end [Auxerre & Inder 86] that can cope with certain kinds of imperatives and temporal questions. The front-end was used to interface to a Prolog database that modelled a blocks-world similar to that of Winograd's SHRDLU [Winograd 73]. The dialogue in (7.14) – (7.19) illustrates the capabilities of Spenceley's system. The user can type imperatives, like (7.14) and (7.15), that cause the database to be updated to reflect the new state of the blocks-world. At any point, questions like (7.16) and (7.18) can be issued, to ask about previous actions or about the current state of the world.

- (7.14) Take Cube1.
- (7.15) Put Cube1 on Cube2.
- (7.16) What was put on Cube2?
- (7.17) Cube1.
- (7.18) Is Cube2 on Cube1?
- (7.19) No.

A simplistic aspectual taxonomy is adopted, that distinguishes between *states* and *actions* (the latter containing Vendler's activities, accomplishments, and achievements; see section 2.2). The linguistic coverage is severely restricted. For example, the user can ask about past actions and present states (e.g. (7.16), (7.18)), but not about past states ((7.20) is rejected). Only “*while ...*”, “*before ...*”, and “*after ...*” subordinate clauses can be used to specify past times, and subordinate clauses can refer only to actions, not states (e.g. (7.21) is allowed, but (7.22) is not). Temporal adverbials, like “*at 5:00pm*” in (7.23), are not supported. Spenceley also attempts to provide some support for *tense anaphora* (section 2.12), but her tense anaphora mechanism is very rudimentary.

- (7.20) × Where was Cube1?
- (7.21) What was taken before Cube1 was put on Cube2?
- (7.22) × What was taken before Cube1 was on Cube2?

(7.23) × What was taken at 5:00pm?

The English requests are parsed using an “extraposition grammar” [Pereira 81], and they are translated into a subset of Prolog that acts as a meaning representation language.² The resulting Prolog expressions are then executed by the Prolog interpreter to update the database or to retrieve the requested information. The “database” is a collection of ad hoc Prolog facts (and in that respect similar to the “databases” of Bruce, De et al., and Moens). It stores information about past actions, but not states (this is probably why questions like (7.22) are not allowed). Also, the database records temporal relations between actions (which action followed which action, which action happened during some other action), but not the specific times where the actions happened. Hence, there is no information in the database to answer questions like (7.23), that require the specific times where the actions happened to be known.

7.1.6 Brown

Brown [Brown 94] describes a question-answering system that can handle some temporal linguistic phenomena. As in Bruce’s system, the user first “teaches” the system various facts (e.g. “*Pedro is beating Chiquita.*”), and he/she can then ask questions about these facts (e.g. “*Is he beating her?*”). Brown’s system is interesting in that it is based on Discourse Representation Theory (DRT), a theory in which tense and aspect have received particular attention [Kamp & Reyle 93]. Brown’s system, however, seems to implement the tense and aspect mechanisms of DRT to a very limited extent. Brown shows only how simple present, simple past, present continuous, and past continuous verb forms can be handled. Other tenses, temporal adverbials, temporal subordinate clauses, etc. do not seem to be supported.

Brown’s system transforms the English sentences into DRT discourse representation structures, using a grammar written in an extended DCG version [Covington 93]. Brown provides very little information about this grammar. The relation of Brown’s grammar to that sketched in [Kamp & Reyle 93] is also unclear. The discourse representation structures are then translated into Prolog facts (this turns out to be relatively straight-forward). As in Moens’ and Spenceley’s systems, the “database” is a collection of Prolog facts, rather than a principled stand-alone system.

² The syntax and semantics of a similar Prolog subset, that is used as the meaning representation language of another version of MASQUE, are defined in [Androutsopoulos 92].

7.1.7 Other related work

Hafner [Hafner 85] considers the inability of existing NLIDBs to handle questions involving time a major weakness. Observing that there is no consensus among database researchers on how the notion of time should be supported in databases (this was true when [Hafner 85] was written), Hafner concludes that NLIDB designers who wish their systems to handle questions involving time cannot look to the underlying DBMS for special temporal support. She therefore proposes a temporal reasoning model (consisting of a temporal ontology, a Prolog-like representation language, and inference rules written in Prolog), intended to be incorporated into a hypothetical NLIDB to compensate for the lack of temporal support from the DBMS. Hafner, however, does not describe exactly how her reasoning model would be embedded into a NLIDB (e.g. how the semantics of verb tenses, temporal adverbials, etc. could be captured in her representation language, how English questions could be translated systematically into her representation language, and exactly how her inference rules would interact with the DBMS). Also, although when [Hafner 85] was written it was true that there was no consensus among temporal database researchers, and that the NLIDB designer could not expect special temporal support from the DBMS, this is (at least to some extent) not true at the present. A temporal database query language (TSQL2) that was designed by a committee comprising most leading temporal database researchers now exists, and a prototype DBMS (TIMEDB; section 1.2.4) that supports TSQL2 has already appeared. Instead of including into the NLITDB a temporal reasoning module (as sketched by Hafner), in this thesis I assumed that a DBMS supporting TSQL2 is available, and I exploited TSQL2's temporal facilities.

Mays [Mays 86] defines a modal logic which can be used to reason about possible or necessary states of the world (what may or will become true, what was or could have been true; see also the discussion on modal questions in section 1.4). Mays envisages a reasoning module based on his logic that would be used when a NLIDB attempts to generate cooperative responses. In (7.25), for example, the system has offered to monitor the database, and to inform the user when Kitty Hawk reaches Norfolk. In order to avoid responses like (7.27), the system must be able to reason that the distance between the two cities will never change. Mays, however, does not discuss exactly how that reasoning module would be embedded into a NLIDB (e.g. how English questions would be mapped to expressions of his logic, and how the reasoning module would

interact with the database).

- (7.24) Is the Kitty Hawk in Norfolk?
- (7.25) No, shall I let you know when she is?
- (7.26) Is New York less than 50 miles from Philadelphia?
- (7.27) No, shall I let you know when it is?

Hinrichs [Hinrichs 88] proposes methods to address some time-related linguistic phenomena, reporting on experience from a natural language understanding system that, among other things, allows the user to access time-dependent information stored in a database. Although Hinrichs' methods are interesting (some of them were discussed in section 2.11), [Hinrichs 88] provides little information on the actual natural language understanding system, and essentially no information on the underlying DBMS and how the intermediate representation language expressions are evaluated against the database. There is also no indication that any aspectual taxonomy is used, and the system uses a version of Montague's PTQ grammar (see related comments in section 7.2.3 below).

Finally, in CLE (a generic natural language front-end [Alshaw 92]) verb tenses introduce into the logical expressions temporal operators, and variables that are intended to represent states or events. The semantics of these operators and variables, however, are left undefined. In CLARE (roughly speaking, a NLIDB based on CLE; see [Alshaw *et al.* 92]) the temporal operators are dropped, and verb tenses are expressed using predications over event or state variables. The precise semantic status of these variables remains obscure. Both [Alshaw 92] and [Alshaw *et al.* 92] do not discuss temporal linguistic phenomena in any detail.

7.2 Assessment

It follows from the discussion in section 7.1 that previous approaches to NLITDBs suffer from one or more of the following: (i) they ignore important English temporal mechanisms, or assign to them over-simplified semantics (e.g. Clifford, Spenceley, Brown), (ii) they lack clearly defined meaning representation languages (e.g. Bruce, De et al., Moens), (iii) they do not provide complete descriptions of the mappings from natural language to meaning representation language (e.g. Bruce, Moens, Brown), or (iv) from

meaning representation language to database language (e.g. Clifford), (v) they adopt idiosyncratic and often not well-defined database models or languages (e.g. Bruce, De et al., Moens, Spenceley, Brown), (vi) they do not demonstrate that their ideas are implementable (e.g. Clifford, Hafner, Mayes). In this section I assess the work of this thesis with respect to (i) – (vi), comparing mainly to Clifford’s work, which constitutes the most significant previous exploration of NLITDBs.

7.2.1 English temporal mechanisms and their semantics

In section 7.1.1, I criticised Clifford’s lack of aspectual taxonomy. It should be clear from the discussion in chapter 2 that the distinction between aspectual classes pertains to the semantics of most temporal linguistic mechanisms, and that without an aspectual taxonomy important semantic distinctions cannot be captured (e.g. the fact that the simple past of a culminating activity verb normally implies that the climax was reached, while the simple past of a point, state, or activity verb carries no such implication; the fact that an “*at ...*” adverbial typically has an inchoative or terminal meaning with a culminating activity, but an interjacent meaning with a state, etc.) The aspectual taxonomy of this thesis allowed me to capture many distinctions of this kind, which cannot be accounted for in Clifford’s framework. Generally, this thesis examined the semantics of English temporal mechanisms at a much more detailed level compared to Clifford’s work. Particular care was also taken to explain clearly which temporal linguistic mechanisms this thesis attempts to support, which simplifications were introduced in the semantics of these mechanisms, and which phenomena remain to be considered (see table 2.9 on page 72 for a summary). This information is difficult to obtain in the case of Clifford’s work.

In terms of syntactic coverage of time-related phenomena, the grammar of this thesis is similar to Clifford’s. Both grammars, for example, support only three kinds of temporal subordinate clauses: “*while ...*”, “*before ...*”, and “*after ...*” clauses. Clifford’s grammar allows simple-future verb forms (these are not supported by the grammar of this thesis), but it does not allow progressive or perfect forms (which are partially supported by the grammar of this thesis). The two grammars allow similar temporal adverbials (e.g. “*in 1991*”, “*before 3/5/90*”, “*yesterday*”), though there are adverbials that are supported by Clifford’s grammar but not by the grammar of this thesis (e.g. “*never*”, “*always*”), and adverbials that are supported by the grammar of this thesis

but not by Clifford's (e.g. "for five hours", "in two days"). Both grammars support yes/no questions, "Who/What/Which ... ?" and "When ... ?" questions, multiple interrogatives (e.g. "Who inspected what on 1/1/91?"), and assertions (which are treated as yes/no questions). The reader is reminded, however, that Clifford assigns to temporal linguistic mechanisms semantics which are typically much shallower than the semantics of this thesis.

Although the framework of this thesis can cope with an interesting set of temporal linguistic phenomena, there are still many English temporal mechanisms that are not covered (e.g. "since ... " adverbials, "when ... " clauses, tense anaphora). Hence, the criticism about previous approaches, that important temporal linguistic mechanisms are not supported, applies to the work of this thesis as well. (It also applies to Clifford's framework, where most of these mechanisms are also not covered.) I claim, however, that the temporal mechanisms that are currently supported are assigned sufficiently elaborate semantics, to the extent that the other criticism about previous approaches, that they use over-simplified semantics, does not apply to the work of this thesis. I hope that further work on the framework of this thesis will extend its coverage of temporal phenomena (see section 8.2 below).

7.2.2 Intermediate representation language

From the discussion in section 7.1, it follows that some previous proposals on NLITDBS (e.g. Bruce, De et al., Moens) use meaning representation languages that are not clearly defined. (Clifford's work does not suffer from this problem; his IL_s language is defined rigorously.) This is a severe problem. Without a detailed description of the syntax of the representation language, it is very difficult to design a mapping from the representation language to a new database language (one may want to use the linguistic front-end with a new DBMS that supports another database language), and to check that existing mappings to database languages cover all the possible expressions of the representation language. Also, without a rigorously defined semantics of the representation language, it is difficult to see the exact semantics that the linguistic front-end assigns to natural language expressions, and it is impossible to prove formally that the mapping from representation language to database language preserves the semantics of the representation language expressions. This pitfall was avoided in this thesis: both the syntax and the semantics of TOP are completely and formally defined

(chapter 3).

7.2.3 Mapping from English to representation language

In section 7.1, I noted that some previous NLITDB proposals (e.g. Bruce, Moens) provide very little or no information on the mapping from English to meaning representation language. (Again, this criticism does not apply to Clifford's work; his mapping from English to IL_s is well-documented.) In this thesis, this pitfall was avoided: I adopted HPSG, a well-documented and currently widely-used grammar theory, and I explained in detail (in chapter 4) all the modifications that were introduced to HPSG, and how HPSG is used to map from English to TOP. I consider the fact that this thesis adopts HPSG to be an improvement over Clifford's framework, which is based on Montague's ageing PTQ grammar, and certainly a major improvement over other previous NLITDB proposals (e.g. Bruce, Spenceley, De et al., Moens) that employ ad hoc grammars which are not built on any principled grammar theory.

7.2.4 Mapping from representation language to database language

As mentioned in section 7.1.1, Clifford outlines an algorithm for translating from IL_s (his intermediate representation language) to a version of relational algebra. This algorithm, however, is described in a very sketchy manner, and there is no proof that the algorithm is correct (i.e. that the generated algebraic expressions preserve the semantics of the IL_s expressions). In contrast, the TOP to TSQL2 mapping of this thesis is defined rigorously, and I have proven formally that it generates appropriate TSQL2 queries (chapter 5 and appendix A).

7.2.5 Temporal database model and language

Several previous proposals on NLITDBS (e.g. De et al., Spenceley, Moens) adopt temporal database models and languages that are idiosyncratic (not based on established database models and languages) and often not well-defined. Although Clifford's database model and algebra are well-defined temporal versions of the traditional relational database model and algebra, they constitute just one of numerous similar proposals in temporal databases, and it is unlikely that DBMSs supporting Clifford's model and algebra will ever appear. This thesis adopted TSQL2 and its underlying

BCDM model. As already noted, TSQL2 was designed by a committee comprising most leading temporal database researchers, and hence it has much better chances of being supported by forthcoming temporal DBMSs, or at least of influencing the models and languages that these DBMSs will support. As mentioned in section 1.2.4, a prototype DBMS for a version of TSQL2 has already appeared. Although I had to introduce some modifications to TSQL2 and BCDM (and hence the database language and model of this thesis diverge from the committee's proposal), these modifications are relatively few and well-documented (chapter 5).

7.2.6 Implementation

As mentioned in section 7.1.1, although a parser for Clifford's PTQ version has been implemented, there is no indication that a translator from IL_s to his relational algebra was ever constructed, or that his framework was ever used to build an actual NLITDB. (Similar comments apply to the work of Hafner and Mays of section 7.1.7.) In contrast, the framework of this thesis was used to implement a prototype NLITDB. Although several modules need to be added to the prototype NLITDB (section 6.6), the existence of this prototype constitutes an improvement over Clifford's work. Unfortunately, the NLITDB of this thesis still suffers from the fact that it has never been linked to a DBMS (section 6.2). I hope that this will be achieved in future (see section 8.2 below).

7.3 Summary

In terms of syntactic coverage of temporal linguistic mechanisms, the framework of this thesis is similar to Clifford's. The semantics that Clifford assigns to these mechanisms, however, are much shallower than those of this thesis. In both frameworks, there are several time-related phenomena that remain to be covered. Unlike some of the previous NLITDB proposals, the intermediate representation language of this thesis (TOP) is defined rigorously, and the mapping from English to TOP is fully documented. Unlike Clifford's and other previous proposals, this thesis adopts a temporal database model and language (TSQL2) that were designed by a committee comprising most leading temporal database researchers, and that are more likely to be supported by (or at least influencing) forthcoming temporal DBMSs. The mapping from TOP to TSQL2 is fully defined and formally proven. In contrast, Clifford's corresponding mapping is specified

in a sketchy way, with no proof of its correctness. Also, unlike Clifford's and other previous proposals, the framework of this thesis was used to implement a prototype NLITDB. The implementation of this thesis still suffers from the fact that the prototype NLITDB has not been linked to a DBMS. I hope, however, that this will be achieved in future.

Chapter 8

Conclusions

“Times change and we with time.”

8.1 Summary of this thesis

This thesis has proposed a principled framework for constructing natural language interfaces to temporal databases (NLITDBs). This framework consists of:

- a formal meaning representation language (TOP), used to represent the semantics of English questions involving time,
- an HPSG version that maps a wide range of English temporal questions to appropriate TOP expressions,
- a set of translation rules that turn TOP expressions into suitable TSQL2 queries.

The framework of this thesis is principled, in the sense that it is clearly defined and based on current ideas from tense and aspect theories, grammar theories, temporal logics, and temporal databases. To demonstrate that it is also workable, it was employed to construct a prototype NLITDB, implemented using ALE and Prolog.

Although several issues remain to be addressed (these are discussed in section 8.2 below), the work of this thesis constitutes an improvement over previous work on NLITDBs, in that: (i) the semantics of English temporal mechanisms are generally examined at a more detailed level, (ii) the meaning representation language is completely and formally defined, (iii) the mapping from English to meaning representation language is well-documented and based on a widely-used grammar theory, (iv) a temporal

database language and model that were designed by a committee comprising most leading temporal database researchers are adopted, (v) the mapping from meaning representation language to database language is clearly defined and formally proven, (vi) it was demonstrated that the theoretical framework of this thesis is implementable, by constructing a prototype NLITDB on which more elaborate systems can be based.

8.2 Further work

There are several ways in which the work of this thesis could be extended:

Extending the linguistic coverage: In section 7.2, I noted that although the framework of this thesis can handle an interesting set of temporal linguistic mechanisms, there are still many time-related linguistic phenomena that are not supported (see table 2.9 on page 72). One could explore how some of these phenomena could be handled. The temporal anaphoric phenomena of section 2.12 are among those that seem most interesting to investigate: several researchers have examined temporal anaphoric phenomena, e.g. [Partee 84], [Hinrichs 86], [Webber 88], [Eberle & Kasper 89], and it would be interesting to explore the applicability of their proposals to NLITDBs. A Wizard of Oz experiment could also be carried out to determine which temporal phenomena most urgently need to be added to the linguistic coverage, and to collect sample questions that could be used as a test suite for NLITDBs [King 96]. (In a Wizard of Oz experiment, users interact through terminals with a person that pretends to be a natural language front-end; see [Diaper 86].)

Cooperative responses: In section 1.4, I noted that the framework of this thesis provides no mechanism for cooperative responses. It became evident during the work of this thesis that such a mechanism is particularly important in NLITDBs and should be added (cases where cooperative responses are needed were encountered in sections 2.5.2, 2.5.3, 2.6, 2.9.2, 2.10.1, 2.10.2, 3.10, and 6.8). To use an example from section 2.5.2, (8.1) is assigned a TOP formula that requires BA737 to have *reached* gate 2 for the answer to be affirmative. This causes a negative response to be generated if BA737 was taxiing to gate 2 but never reached it. While a simple negative response is strictly speaking correct, it is hardly satisfactory in this case. A more cooperative response like (8.2) is needed.

(8.1) Did BA737 taxi to gate 2?

(8.2) BA737 was taxiing to gate 2 but never reached it.

In other cases, the use of certain English expressions reveals a misunderstanding of how situations are modelled in the database and the NLITDB. In (8.3), for example, the “for ... ” adverbial shows that the user considers departures to have durations (perhaps because he/she considers the boarding part of the departure; see section 2.4.2). In the airport application, however, departures are treated as instantaneous (they include only the time-points where the flights leave the gates), and “to taxi” is classified as a point verb. The “for ... ” adverbial combines with a point expression, which is not allowed in the framework of this thesis (see table 2.4 on page 52). This causes (8.3) to be rejected without any explanation to the user. It would be better if a message like (8.4) could be generated.

(8.3) Which flight was departing for twenty minutes?

(8.4) Departures of flights are modelled as instantaneous.

Paraphrases: As explained in section 6.2, a mechanism is needed to generate English paraphrases of possible readings in cases where the NLITDB understands a question to be ambiguous.

Optimising the TSQL2 queries: As discussed in section 5.12, there are ways in which the generated TSQL2 queries could be optimised before submitting them to the DBMS. One could examine exactly how these optimisations would be carried out.

Additional modules in the prototype NLITDB: Section 6.6 identified several modules that would have to be added to the prototype NLITDB if this were to be used in real-life applications: a preprocessor, modules to handle quantifier scoping and anaphora resolution, an equivalential translator, and a response generator. Adding a preprocessor and a simplistic response generator (as described at the beginning of section 6.6.5) should be easy, though developing a response generator that would produce cooperative responses is more complicated (see the discussion above and section 6.6.5). It should also be possible to add an equivalential translator without introducing major revisions in the work of this thesis. In contrast, adding modules to handle quantifier

scoping and anaphora requires extending first the theoretical framework of this thesis: one has to modify TOP to represent universal quantification, unresolved quantifiers, and unresolved anaphoric expressions (sections 6.6.2 and 6.6.3), and to decide how to determine the scopes or referents of unresolved quantifiers and anaphoric expressions.

Linking to a DBMS: As explained in sections 1.2.4 and 1.3, a prototype DBMS (TIMEDB) that supports a version of TSQL2 was released recently, but the prototype NLITDB of this thesis has not been linked to that system (or any other DBMS). Obviously, it would be particularly interesting to connect the NLITDB of this thesis to TIMEDB. This requires bridging the differences between the versions of TSQL2 that the two systems adopt (section 1.3).

Embedding ideas from this thesis into existing NLIDBs: Finally, one could explore if ideas from this thesis can be used in existing natural language front-ends. In section 7.1.7, for example, I noted that CLE's formulae contain temporal operators whose semantics are undefined. One could examine if TOP operators (whose semantics are formally defined) could be used instead. Ideas from the TOP to TSQL2 mapping of chapter 5 could then be employed to translate the resulting CLE formulae into TSQL2.

Bibliography

- [Allen 83] J.F. Allen. Maintaining Knowledge about Temporal Intervals. *Communications of the ACM*, 26(11):832–843, 1983.
- [Allen 84] J.F. Allen. Towards a General Theory of Action and Time. *Artificial Intelligence*, 23:123–154, 1984.
- [Alshawhi 92] H. Alshawhi, editor. *The Core Language Engine*. MIT Press, Cambridge, Massachusetts, 1992.
- [Alshawhi *et al.* 92] H. Alshawhi, D. Carter, R. Crouch, S. Pulman, M. Rayner, and A. Smith. CLARE – A Contextual Reasoning and Cooperative Response Framework for the Core Language Engine. Final report, SRI International, 1992.
- [Androutsopoulos 92] I. Androutsopoulos. Interfacing a Natural Language Front-End to a Relational Database. MSc thesis, Department of Artificial Intelligence, University of Edinburgh, 1992.
- [Androutsopoulos *et al.* 93] I. Androutsopoulos, G. Ritchie, and P. Thanisch. An Efficient and Portable Natural Language Query Interface for Relational Databases. In P.W. Chung, G. Lovegrove, and M. Ali, editors, *Proceedings of the 6th International Conference on Industrial & Engineering Applications of Artificial Intelligence and Expert Systems, Edinburgh*, pages 327–330. Gordon and Breach Publishers Inc., Langhorne, PA, U.S.A., 1993.
- [Androutsopoulos *et al.* 95a] I. Androutsopoulos, G.D. Ritchie, and P. Thanisch. Experience Using TSQL2 in a Natural Language Interface. In J. Clifford and A. Tuzhilin, editors, *Recent Advances in Temporal Databases – Proceedings of the International Workshop on Temporal Databases, Zurich, Switzerland*, Workshops in Computing, pages 113–132. Springer-Verlag, Berlin, 1995.
- [Androutsopoulos *et al.* 95b] I. Androutsopoulos, G.D. Ritchie, and P. Thanisch. Natural Language Interfaces to Databases – An Intro-

- duction. *Natural Language Engineering*, 1(1):29–81, 1995.
- [Ariav 86] G. Ariav. A Temporally Oriented Data Model. *ACM Transactions on Database Systems*, 11(4):499–527, 1986.
- [Auxerre & Inder 86] P. Auxerre and R. Inder. MASQUE Modular Answering System for Queries in English – User’s Manual. Technical Report AIAI/SR/10, Artificial Intelligence Applications Institute, University of Edinburgh, 1986.
- [Barros & De Roeck 94] F.A. Barros and A. De Roeck. Resolving Anaphora in a Portable Natural Language Front End to a Database. In *Proceedings of the 4th Conference on Applied Natural Language Processing, Stuttgart, Germany*, pages 119–124, 1994.
- [Blackburn *et al.* 94] P. Blackburn, C. Gardent, and M. de Rijke. Back and Forth through Time and Events. In D.M. Gabbay, editor, *Temporal Logic – Proceedings of the First International Conference, ICTL ’94, Bonn, Germany*, number 827 in Lecture Notes in Artificial Intelligence, pages 225–237. Springer-Verlag, Berlin, 1994.
- [Boehlen 95] M.H. Boehlen. Temporal Database System Implementations. Unpublished document, Department of Mathematics and Computer Science, Aalborg University, 1995.
- [Boehlen *et al.* 96] M.H. Boehlen, J. Chomicki, R.T. Snodgrass, and D. Toman. Querying TSQL2 Databases with Temporal Logic. In *Proceedings of the International Conference on Extended Database Technology*, 1996.
- [Bolour *et al.* 83] A. Bolour, T.L. Anderson, L.J. Dekeyser, and H.K.T. Wong. The Role of Time in Information Processing: A Survey. *ACM SIGMOD Record*, 12(3):27–50, 1983.
- [Brent 90] M.R. Brent. A Simplified Theory of Tense Representations and Constraints on their Composition. In *Proceedings of the 28th Annual Meeting of ACL, Pittsburgh, Pennsylvania*, pages 119–126, 1990.
- [Brown 94] D.W. Brown. A Natural Language Querying System Based on Discourse Representation Theory and Incorporating Event Semantics. Technical Report AI-1994-03, Artificial Intelligence Center, University of Georgia, 1994.

- [Bruce 72] B.C. Bruce. A Model for Temporal References and Its Application in a Question Answering Program. *Artificial Intelligence*, 3:1–25, 1972.
- [Brusoni *et al.* 95] V. Brusoni, L. Console, and P. Terenziani. Extending Temporal Relational Databases to Deal with Imprecise and Qualitative Information. In J. Clifford and A. Tuzhilin, editors, *Recent Advances in Temporal Databases – Proceedings of the International Workshop on Temporal Databases, Zurich, Switzerland*, Workshops in Computing, pages 3–22. Springer-Verlag, Berlin, 1995.
- [Calder *et al.* 94] J. Calder, K. Humphreys, and M. Reape. Pleuk – A Shell for Grammar Development Systems. HCRC, University of Edinburgh, and Trinity College Dublin, 1994.
- [Carpenter & Penn 94] B. Carpenter and G. Penn. The Attribute Logic Engine – User’s Guide. Unpublished document, Philosophy Department, Carnegie Mellon University, December 1994.
- [Carpenter 92] B. Carpenter. *The Logic of Typed Feature Structures*. Number 32 in Cambridge Tracts in Theoretical Computer Science. Cambridge University Press, 1992.
- [Cerccone *et al.* 93] N. Cerccone, P. McFetridge, F. Popowich, D. Fass, C. Groeneboer, and G. Hall. The SystemX Natural Language Interface: Design, Implementation, and Evaluation. Technical Report CSS-IS TR 93-03, Centre for Systems Science, Simon Fraser University, Burnaby, BC, Canada, 1993.
- [Clifford & Warren 83] J. Clifford and D.S. Warren. Formal Semantics for Time in Databases. *ACM Transactions on Database Systems*, 8(2):215–254, 1983.
- [Clifford 87a] J. Clifford. Natural Language Querying of Historical Databases. Working Paper CRIS 152, GBA 87-37, Center for Research on Information Systems, Information Systems Area, Graduate School of Business Administration, New York University, 1987.
- [Clifford 87b] J. Clifford. Natural Language Querying of Historical Databases – The QE-III Language Definition and Examples. Working Paper CRIS 164, GBA 87-90, Center for Research on Information Systems, Information Systems Area, Graduate School of Business Administration, New York University, 1987.

- [Clifford 88] J. Clifford. Natural Language Querying of Historical Databases. *Computational Linguistics*, 14(4):10–34, 1988.
- [Clifford 90] J. Clifford. *Formal Semantics and Pragmatics for Natural Language Querying*. Cambridge Tracts in Theoretical Computer Science, Cambridge University Press, Cambridge, England, 1990.
- [Clocksin & Mellish 94] W.F. Clocksin and C.S. Mellish. *Programming in Prolog*. Springer-Verlag, Berlin, 4th edition edition, 1994.
- [Codd 70] E.F. Codd. A Relational Model for Large Shared Data Banks. *Communications of the Association of Computing Machinery*, 13(6):377–387, 1970.
- [Comrie 76] B. Comrie. *Aspect*. Cambridge University Press, Cambridge, England, 1976.
- [Comrie 85] B. Comrie. *Tense*. Cambridge University Press, Cambridge, England, 1985.
- [Cooper *et al.* 90] R. Cooper, K. Mukai, and J. Perry, editors. *Situation Theory and Its Applications*, number 22 in CSLI Lecture Notes. Center for the Study of Language and Information, Stanford, 1990.
- [Copestake & Sparck Jones 90] A. Copestake and K. Sparck Jones. Natural Language Interfaces to Databases. *The Knowledge Engineering Review*, 5(4):225–249, 1990.
- [Covington 93] M. Covington. Brief Notes on GULP 3. Technical report, Artificial Intelligence Programs, University of Georgia, 1993.
- [Crouch & Pulman 93] R.S. Crouch and S.G. Pulman. Time and Modality in a Natural Language Interface to a Planning System. *Artificial Intelligence*, 63:265–304, 1993.
- [Crouch 91] R.S. Crouch. Time, Natural Language and Planning Systems. In P. Ohrstrom, editor, *Time in Science, Language and History: An Interdisciplinary Research Seminar*, pages 38–59. Institut for Kommunikation, Aalborg Universitetscenter, 1991.
- [Dalrymple 88] M. Dalrymple. The Interpretation of Tense and Aspect in English. In *In Proceedings of the 26th Annual Meeting of ACL*, pages 68–74, 1988.
- [Davidson & Kaplan 83] J. Davidson and S.J. Kaplan. Natural Language Access to Data Bases: Interpreting Update Requests. *Computational Linguistics*, 9(2):57–68, 1983.

- [Davies *et al.* 95] C. Davies, B. Lazell, M. Hughes, and L. Cooper. Time is Just Another Attribute – or at Least, Just Another Dimension. In J. Clifford and A. Tuzhilin, editors, *Recent Advances in Temporal Databases – Proceedings of the International Workshop on Temporal Databases, Zurich, Switzerland*, Workshops in Computing, pages 175–193. Springer-Verlag, Berlin, 1995.
- [De *et al.* 85] S. De, S. Pan, and A.B. Whinston. Natural Language Query Processing in a Temporal Database. *Data & Knowledge Engineering*, 1:3–15, 1985.
- [De *et al.* 87] S. De, Pan S., and A.B. Whinston. Temporal Semantics and Natural Language Processing in a Decision Support System. *Information Systems*, 12(1):29–47, 1987.
- [De Roeck & Lowden 86] A.N. De Roeck and B.G.T. Lowden. Generating English Paraphrases from Formal Relational Calculus Expressions. In *Proceedings of the 11th International Conference on Computational Linguistics, Bonn, Germany*, pages 581–583, 1986.
- [Diaper 86] D. Diaper. Identifying the Knowledge Requirements of an Expert System’s Natural Language Processing Interface. In M.D. Harrison and A.F. Monk, editors, *People and Computers: Designing for Usability – Proceedings of the Second Conference of the British Computer Society, Human Computer Interaction Specialist Group, University of York*, pages 263–280. Cambridge University Press, 1986.
- [Dowty 77] D.R. Dowty. Toward a Semantic Analysis of Verb Aspect and the English ‘Imperfective’ Progressive. *Linguistics and Philosophy*, 1:45–77, 1977.
- [Dowty 82] D.R. Dowty. Tenses, Time Adverbs, and Compositional Semantic Theory. *Linguistics and Philosophy*, 5:23–55, 1982.
- [Dowty 86] D.R. Dowty. The Effects of Aspectual Class on the Temporal Structure of Discourse: Semantics or Pragmatics? *Linguistics and Philosophy*, 9:37–61, 1986.
- [Dowty *et al.* 81] D.R. Dowty, R.E. Wall, and S. Peters. *Introduction to Montague Semantics*. D.Reidel Publishing Company, Dordrecht, Holland, 1981.
- [Draxler 92] C. Draxler. *Accessing Relational and Higher Databases through Database Set Predicates in Logic Programming Languages*. PhD thesis, University of Zurich, 1992.

- [Eberle & Kasper 89] K. Eberle and W. Kasper. Tenses as Anaphora. In *Proceedings of the 4th Conference of the European Chapter of ACL, Manchester, England*, pages 43–50, 1989.
- [Enc 86] M. Enc. Towards a Referential Analysis of Temporal Expressions. *Linguistics and Philosophy*, 9:405–426, 1986.
- [Gabbay *et al.* 94] D.M. Gabbay, I. Hodkinson, and M. Reynolds. *Temporal Logic: Mathematical Foundations and Computational Aspects*. Oxford University Press, 1994.
- [Gadia 88] S.K. Gadia. A Homogeneous Relational Model and Query Languages for Temporal Databases. *ACM Transactions on Database Systems*, 13(4):418–448, 1988.
- [Gazdar & Mellish 89] G. Gazdar and C. Mellish. *Natural Language Processing in Prolog*. Addison-Wesley, Wokingham, England, 1989.
- [Gertz & Lipeck 95] M. Gertz and U.W. Lipeck. Temporal Integrity Constraints in Temporal Databases. In J. Clifford and A. Tuzhilin, editors, *Recent Advances in Temporal Databases – Proceedings of the International Workshop on Temporal Databases, Zurich, Switzerland*, Workshops in Computing, pages 77–92. Springer-Verlag, Berlin, 1995.
- [Ginzburg 92] J. Ginzburg. *Questions, Queries, and Facts: A Semantics and Pragmatics for Interrogatives*. PhD thesis, Stanford University, 1992.
- [Ginzburg 95a] J. Ginzburg. Resolving Questions, I. *Linguistics and Philosophy*, 18(5):459–427, 1995.
- [Ginzburg 95b] J. Ginzburg. Resolving Questions, II. *Linguistics and Philosophy*, 18(6):567–609, 1995.
- [Grosz *et al.* 87] B.J. Grosz, D.E. Appelt, P.A. Martin, and F.C.N. Pereira. TEAM: An Experiment in the Design of Transportable Natural-Language Interfaces. *Artificial Intelligence*, 32:173–243, 1987.
- [Hafner 85] C.D. Hafner. Semantics of Temporal Queries and Temporal Data. In *Proceedings of the 23rd Annual Meeting of ACL, Chicago, Illinois*, pages 1–8, 1985.
- [Harper & Charniak 86] M.P. Harper and E. Charniak. Time and Tense in English. In *Proceedings of the 24th Annual Meeting of ACL, New York*, pages 3–9, 1986.

- [Hinrichs 86] E. Hinrichs. Temporal Anaphora in Discourses of English. *Linguistics and Philosophy*, 9:63–82, 1986.
- [Hinrichs 88] E.W. Hinrichs. Tense, Quantifiers, and Contexts. *Computational Linguistics*, 14(2):3–14, 1988.
- [Hirst 81] G. Hirst. *Anaphora in Natural Language Understanding: A Survey*. Springer-Verlag, Berlin, 1981.
- [Hobbs 86] J.R. Hobbs. Resolving Pronoun References. In B.J. Grosz, K. Sparck Jones, and B.L. Webber, editors, *Readings in Natural Language Processing*, pages 339–352. Morgan Kaufmann, San Mateo, CA, 1986.
- [Hwang & Schubert 94] C.H. Hwang and K. Schubert. Interpreting Tense, Aspect and Time Adverbials: A Compositional, Unified Approach. In D.M. Gabbay and H.J. Ohlbach, editors, *Proceedings of the First International Conference on Temporal Logic, Bonn*, number 827 in Lecture Notes in Artificial Intelligence, pages 238–264. Springer-Verlag, Berlin, 1994.
- [Jensen *et al.* 93] C.S. Jensen, J. Clifford, R. Elmasri, S.K. Gadia, P. Hayes, S. Jajodia, C. Dyreson, F. Grandi, W. Kaefer, N. Kline, N. Lorentzos, Y. Mitsopoulos, A. Montanari, D. Nonen, E. Peressi, B. Pernici, J. Roddick, N.L. Sarda, M.R. Scalas, A. Segev, R.T. Snodgrass, M.D. Soo, A. Tansel, P. Tiberio, and G. Wiederhold. A Consensus Glossary of Temporal Database Concepts. Technical Report R-93-2035, Institute for Electronic Systems, Department of Mathematics and Computer Science, Aalborg University, Denmark, 1993. Earlier version in *SIGMOD Record*, 21(3):35–43, September 1992.
- [Johnson 85] T. Johnson. *Natural Language Computing: The Commercial Applications*. Ovum Ltd., London, 1985.
- [Kameyama *et al.* 93] M. Kameyama, R. Passonneau, and M. Poesio. Temporal Centering. In *Proceedings of the 31st Annual Meeting of ACL, Columbus, Ohio*, 1993.
- [Kamp & Reyle 93] H. Kamp and U. Reyle. *From Discourse to Logic*. Kluwer Academic Publishers, 1993.
- [Kaplan 82] S.J. Kaplan. Cooperative Responses from a Portable Natural Language Data Base Query System. *Artificial Intelligence*, 19:165–187, 1982.
- [Kenny 63] A. Kenny. *Action, Emotion and Will*. Routledge and K. Paul, London, 1963.

- [Kent 93] S. Kent. *Modelling Events from Natural Language*. PhD thesis, Imperial College of Science Technology and Medicine, 1993.
- [King 96] M. King. Evaluating Natural Language Processing Systems. *Communications of the ACM*, 39(1):73–79, 1996.
- [Kline 93] N. Kline. An Update of the Temporal Database Bibliography. *ACM SIGMOD Record*, 22(4):66–80, 1993.
- [Koubarakis 95] M. Koubarakis. Databases and Temporal Constraints: Semantics and Complexity. In J. Clifford and A. Tuzhilin, editors, *Recent Advances in Temporal Databases – Proceedings of the International Workshop on Temporal Databases, Zurich, Switzerland, Workshops in Computing*, pages 93–109. Springer-Verlag, Berlin, 1995.
- [Kowalski & Sergot 86] R. Kowalski and M. Sergot. A Logic-based Calculus of Events. *New Generation Computing*, 4:67–95, 1986.
- [Lascarides & Oberlander 93] A. Lascarides and J. Oberlander. Temporal Connectives in a Discourse Context. In *Proceedings of the 6th Conference of the European Chapter of ACL, Utrecht, The Netherlands*, pages 260–268, 1993.
- [Lascarides 88] A. Lascarides. *A Formal Semantic Analysis of the Progressive*. PhD thesis, University of Edinburgh, 1988.
- [Lindop 86] J.D. Lindop. Enhancements to a Natural Language Front End. MSc thesis, Department of Artificial Intelligence, University of Edinburgh, 1986.
- [Lorentzos & Johnson 88] N.A. Lorentzos and R.G. Johnson. Extending Relational Algebra to Manipulate Temporal Data. *Information Systems*, 13(3):289–296, 1988.
- [Lowden & De Roeck 86] B.G.T. Lowden and A.N. De Roeck. REMIT: A Natural Language Paraphraser for Relational Query Expressions. *ICL Technical Journal*, 5(1):32–45, 1986.
- [Lowden *et al.* 91a] B.G.T. Lowden, B.R. Walls, A.N. De Roeck, C.J. Fox, and R. Turner. A Formal Approach to Translating English into SQL. In Jackson and Robinson, editors, *Proceedings of the 9th British National Conference on Databases (BNCOD)*, 1991.
- [Lowden *et al.* 91b] B.G.T. Lowden, B.R. Walls, A.N. De Roeck, C.J. Fox, and R. Turner. Modal Reasoning in Relational Systems. Technical Report CSM-163, Dept. of Computer Science, University of Essex, 1991.

- [Lucas 88] R. Lucas. *Database Applications Using Prolog*. Halsted Press, 1988.
- [Mays 86] E. Mays. A Temporal Logic for Reasoning about Changing Data Bases in the Context of Natural Language Question-Answering. In L. Kerschberg, editor, *Expert Database Systems – Proceedings of the First International Workshop*, pages 559–578. Benjamin/Cummings, California, 1986.
- [McCarthy & Hayes 69] J. McCarthy and P.J. Hayes. Some Philosophical Problems from the Standpoint of Artificial Intelligence. In *Machine Intelligence 4*, pages 463–502. Edinburgh University Press, 1969.
- [McDermott 82] D. McDermott. A Temporal Logic for Reasoning about Processes and Plans. *Cognitive Science*, 6:101–155, 1982.
- [McKenzie & Snodgrass 90] E. McKenzie and R. Snodgrass. Schema Evolution and the Relational Algebra. *Information Systems*, 15(2):207–232, 1990.
- [McKenzie & Snodgrass 91] E. McKenzie and R. Snodgrass. Evaluation of Relational Algebras Incorporating the Time Dimension in Databases. *ACM Computing Surveys*, 23(4):501–543, 1991.
- [McKenzie 86] E. McKenzie. Bibliography: Temporal Databases. *ACM SIGMOD Record*, 15(4):40–52, 1986.
- [Melton & Simon 93] J. Melton and A.R. Simon. *Understanding the New SQL: A Complete Guide*. Morgan Kaufmann Publishers, San Mateo, California, 1993.
- [Moens & Steedman 88] M. Moens and M. Steedman. Temporal Ontology and Temporal Reference. *Computational Linguistics*, 14(2):15–28, 1988.
- [Moens 87] M. Moens. *Tense, Aspect and Temporal Reference*. PhD thesis, University of Edinburgh, 1987.
- [Moens 88] M. Moens. Temporal Databases and Natural Language. In C. Rolland, F. Bodart, and M. Leonard, editors, *Proceedings of Working Conference on Temporal Aspects in Information Systems, Sophia-Antipolis, France*, pages 171–183. Elsevier Science Publishers, 1988.
- [Mourelatos 78] A.P.D. Mourelatos. Events, Processes, and States. *Linguistics and Philosophy*, 2:415–434, 1978.

- [Navathe & Ahmed 88] S.B. Navathe and R. Ahmed. TSQL: A Language Interface for History Databases. In C. Rolland, F. Bordart, and M. Leonard, editors, *Working Conference on Temporal Aspects in Information Systems, Sophia-Antipolis, France*, pages 109–122. Elsevier Science Publishers, 1988.
- [Parsons 89] T. Parsons. The Progressive in English: Events, states and Processes. *Linguistics and Philosophy*, 12:213–241, 1989.
- [Parsons 90] T. Parsons. *Events in the Semantics of English: A Study in Subatomic Semantics*. MIT Press, 1990.
- [Partee 84] B.H. Partee. Nominal and Temporal Anaphora. *Linguistics and Philosophy*, 7:243–286, 1984.
- [Passonneau 88] R.J. Passonneau. A Computational Model of the Semantics of Tense and Aspect. *Computational Linguistics*, 14(2):44–60, 1988.
- [Pereira & Warren 80] F. Pereira and D.H.D. Warren. Definite Clause Grammars for Language Analysis – A Survey of the Formalism and a Comparison with Augmented Transition Networks. *Artificial Intelligence*, 13:231–278, 1980.
- [Pereira 81] F. Pereira. Extraposition Grammars. *Computational Linguistics*, 7(4), 1981.
- [Perrault & Grosz 88] C.R. Perrault and B.J. Grosz. Natural Language Interfaces. In H.E. Shrobe, editor, *Exploring Artificial Intelligence*, pages 133–172. Morgan Kaufmann Publishers Inc., San Mateo, California, 1988.
- [Pirie *et al.* 90] N. Pirie, B. Crabtree, R. Crouch, S. Pulman, D. Mofat, G. Ritchie, and A. Tate. A Natural Language Interface to an Intelligent Planning System – System Documentation. Technical Paper 5, Department of Artificial Intelligence, University of Edinburgh, 1990.
- [Pollard & Sag 87] C. Pollard and I.A. Sag. *Information-Based Syntax and Semantics – Volume 1, Fundamentals*. Center for the Study of Language and Information, Stanford, 1987.
- [Pollard & Sag 94] C. Pollard and I.A. Sag. *Head-Driven Phrase Structure Grammar*. University of Chicago Press and Center for the Study of Language and Information, Stanford., 1994.
- [Popowich & Vogel 91] F. Popowich and C. Vogel. The HPSG-PL System. Technical report CSS-IS TR 91-08/CMPT TR 91-08,

- Centre for Systems Science and School of Computing Science, Simon Fraser University, 1991.
- [Pratt & Bree 95] I. Pratt and D.S. Bree. An Approach to the Semantics of some English Temporal Constructions. In *Proceedings of the 17th Annual Conference of the Cognitive Science Society*, Workshops in Computing, pages 118–123. Lawrence Earlbaum Associates, 1995.
- [Prior 67] A. Prior. *Past, Present and Future*. Oxford University Press, Oxford, England, 1967.
- [Rayner 93] Manny Rayner. *Abductive Equivalential Translation and its Application to Natural Language Database Interfacing*. PhD thesis, Stockholm University/Royal College of Technology, 1993.
- [Reichenbach 47] H. Reichenbach. *Elements of Symbolic Logic*. Collier-Macmillan, London, 1947.
- [Richards *et al.* 89] B. Richards, I. Bethke, J. van der Does, and J. Oberlander. *Temporal Representation and Inference*. Cognitive Science Series, Academic Press, Harcourt Brace Jovanovich Publishers, 1989.
- [Ritchie 79] G.D. Ritchie. Temporal Clauses in English. *Theoretical Linguistics*, 6(1):87–115, 1979.
- [Seldrup 95] I. Seldrup. A Customisable HPSG-based Natural Language Front-End. MSc thesis, Department of Artificial Intelligence, University of Edinburgh, 1995.
- [Shieber 86] S.M. Shieber. *An Introduction to Unification-Based Approaches to Grammar*. CSLI, Stanford, 1986.
- [Singh & Singh 92] M. Singh and M.P. Singh. Computing the Temporal Structure of Events in Natural Language. In B. Neumann, editor, *Proceedings of the 10th European Conference on Artificial Intelligence*, pages 528–532. John Wiley & Sons, 1992.
- [Smith 86] C.S. Smith. A Speaker-based Approach to Aspect. *Linguistics and Philosophy*, 9:97–115, 1986.
- [Snodgrass 87] R.T. Snodgrass. The Temporal Query Language TQuel. *ACM Transactions on Database Systems*, 12(2):247–298, 1987.
- [Snodgrass 95] R.T. Snodgrass, editor. *The TSQL2 Temporal Query Language*. Kluwer Academic Publishers, 1995.

- [Snodgrass *et al.* 94a] R.T. Snodgrass, I. Ahn, G. Ariav, D. Batory, J. Clifford, C.E. Dyreson, R. Elmasri, F. Grandi, Jensen C.S., W. Kaefer, N. Kline, K. Kulkarni, T.Y.C. Leung, N. Lorentzos, J.F. Roddick, A. Segev, M.D. Soo, and S.M. Sripada. TSQL2 Language Specification. *SIGMOD Record*, 23(1):65–86, 1994.
- [Snodgrass *et al.* 94b] R.T. Snodgrass, I. Ahn, G. Ariav, P. Bayer, J. Clifford, C. Dyreson, F. Grandi, L. Hermosilla, C.S. Jensen, W. Kafer, N. Kline, T.Y.C. Leung, N. Lorentzos, Y. Mitsopoulos, J.F. Roddick, M. Soo, and S.M. Sripada. An Evaluation of TSQL2. Unpublished TSQL2 commentary, October 1994.
- [Soo 91] M. Soo. Bibliography on Temporal Databases. *ACM SIGMOD Record*, 20(1):14–23, 1991.
- [Spenceley 89] S. Spenceley. Imperatives and Temporal Question Answering in an English Language Front-End. MSc thesis, Department of Artificial Intelligence, University of Edinburgh, 1989.
- [Sripada *et al.* 94] S.M. Sripada, B.L. Rosser, J.M. Bedford, and R.A. Kowalski. Temporal Database Technology for Air Traffic Flow Management. In *Proceedings of the First International Conference on Applications of Databases, Vadstena, Sweden*, pages 28–41. Springer-Verlag, Berlin, 1994.
- [Stam & Snodgrass 88] R. Stam and R. Snodgrass. A Bibliography on Temporal Databases. *IEEE Database Engineering*, 7(4):231–239, 1988.
- [Sterling & Shapiro 94] L. Sterling and E.Y. Shapiro. *The Art of Prolog – Advanced Programming Techniques*. MIT Press, Cambridge, Massachusetts, 2nd edition edition, 1994.
- [Stirling 85] L. Stirling. Distributives, Quantifiers and a Multiplicity of Events. In *Proceedings of the 2nd Conference of the European Chapter of ACL, Geneva, Switzerland*, pages 16–24, 1985.
- [Tansel 86] A.U. Tansel. Adding Time Dimension to Relational Model and Extending Relational Algebra. *Information Systems*, 11(4):343–355, 1986.
- [Tansel *et al.* 93] A. Tansel, J. Clifford, S.K. Gadia, S. Jajodia, A. Segev, and R.T. Snodgrass. *Temporal Databases – Theory, Design, and Implementation*. Benjamin/Cummings, California, 1993.

- [terMeulen 94] A. ter Meulen. Situated Reasoning with Temporal Anaphora. In D.M. Gabbay and H.J. Ohlbach, editors, *Proceedings of the First International Conference on Temporal Logic, Bonn*, number 827 in Lecture Notes in Artificial Intelligence, pages 42–48. Springer-Verlag, Berlin, 1994.
- [Thomson & Martinet 86] A.J. Thomson and A.V. Martinet. *A Practical English Grammar (fourth edition)*. Oxford University Press, 1986.
- [Tsotras & Kumar 96] V.J. Tsotras and A. Kumar. Temporal Database Bibliography Update. *ACM SIGMOD Record*, 25(1), 1996.
- [Ullman 88] J.D. Ullman. *Principles of Database and Knowledge-Base Systems— Volume 1*. Computer Science Press, Rockville, Maryland, 1988.
- [Van Gelder & Topor 91] A. Van Gelder and R.W. Topor. Safety and Translation of Relational Calculus Queries. *ACM Transactions on Database Systems*, 16(2):235–278, 1991.
- [vanBenthem 83] J.F.A.K. van Benthem. *The Logic of Time*. D.Reidel Publishing Company, Dordrecht, Holland, 1983.
- [Vendler 67] Z. Vendler. Verbs and Times. In *Linguistics in Philosophy*, chapter 4, pages 97–121. Cornell University Press, Ithaca, NY, 1967.
- [Vila 94] L. Vila. A Survey on Temporal Reasoning in Artificial Intelligence. *AI Communications*, 7(1):4–28, 1994.
- [Vlach 93] F. Vlach. Temporal Adverbials, Tenses and the Perfect. *Linguistics and Philosophy*, 16:231–283, 1993.
- [Webber 88] B.L. Webber. Tense as Discourse Anaphor. *Computational Linguistics*, 14(2):61–73, 1988.
- [Wijsen 95] J. Wijsen. Design of Temporal Relational Databases Based on Dynamic and Temporal Functional Dependencies. In J. Clifford and A. Tuzhilin, editors, *Recent Advances in Temporal Databases – Proceedings of the International Workshop on Temporal Databases, Zurich, Switzerland*, Workshops in Computing, pages 61–76. Springer-Verlag, Berlin, 1995.
- [Winograd 73] T. Winograd. A Procedural Model of Language Understanding. In R.C. Schank and K.M. Colby, editors, *Computer Models of Thought and Language*. Freeman, San Francisco, 1973.

[Yip 85]

K.M. Yip. Tense, Aspect and the Cognitive Representation of Time. In *Proceedings of the 23rd Annual Meeting of ACL, Chicago*, pages 18–26, 1985.

Appendix A

Translation rules and proofs for chapter 5

A.1 Introduction

This appendix contains the full set of TOP to TSQL2 translation rules, and the proofs of theorems 5.1 and 5.2 (see chapter 5). As noted in section 5.10, the translation rules specify the values of $trans(\phi, \lambda)$ for every TOP formula ϕ and TSQL2 value expression λ . (In practice, λ always represents a period.) There are two kinds of translation rules: (a) base (non-recursive) rules that define the values of $trans(\phi, \lambda)$ when ϕ is an atomic formula or a formula of the form $Culm[\pi(\tau_1, \dots, \tau_n)]$; and (b) recursive rules that define the values of $trans(\phi, \lambda)$ in all other cases (where ϕ is non-atomic), by recursively calling other translation rules to translate subformulae of ϕ .

Section A.3 lists the translation rules for yes/no formulae ϕ . According to section 5.10, these rules have to satisfy theorem 5.2. Theorem 5.2 is proven by induction on the syntactic complexity of ϕ . I first prove that theorem 5.2 holds if ϕ is a predicate $\pi(\tau_1, \dots, \tau_n)$ or a formula of the form $Culm[\pi(\tau_1, \dots, \tau_n)]$. For all other yes/no formulae ϕ , ϕ is non-atomic. In those cases, I prove that theorem 5.2 holds if it holds for all the subformulae of ϕ . Each translation rule of section A.3 is followed by the corresponding part of theorem 5.2's proof. For example, the translation rule that specifies the values of $trans(\phi, \lambda)$ when $\phi = Pres[\phi']$ is followed by the proof that theorem 5.2 holds for $\phi = Pres[\phi']$ if it holds for $\phi = \phi'$.

Section A.4 lists the translation rules for wh-formulae. These rules have to satisfy theorem 5.1 (see section 5.10). There are two translation rules for wh-formulae, that correspond to the case where $\phi \in WHFORMS_1$ or $\phi \in WHFORMS_2$ (see section 3.2). Each rule is followed by a proof that theorem 5.1 holds if $\phi \in WHFORMS_1$ or $\phi \in WHFORMS_2$ respectively.

In the rest of this appendix, I use the term TSQL2 *expression* to refer to any piece of TSQL2 code. In contrast, the term TSQL2 *value expression* is used to refer to a piece of TSQL2 code that normally evaluates to an element of D (section 5.4).

A.2 Lemmata

The following lemmata will prove useful in the following sections.

Lemma A.1 If ξ is a TSQL2 expression, and $\xi_1, \xi_2, \xi_3, \dots, \xi_k$ are substrings of ξ , and any free column reference in ξ is situated within ξ_1 or ξ_2 or ξ_3 or \dots or ξ_k , then:

$$FCN(\xi) \subseteq FCN(\xi_1) \cup FCN(\xi_2) \cup FCN(\xi_3) \cup \dots \cup FCN(\xi_k)$$

Proof: Let us assume that $\alpha \in FCN(\xi)$, i.e. α is a correlation name that has a free column reference ζ in ξ . We need to show that $\alpha \in FCN(\xi_1) \cup \dots \cup FCN(\xi_k)$.

Since ζ is a free column reference in ξ , according to the hypothesis for some $i \in \{1, 2, 3, \dots, k\}$, ζ is situated within ξ_i . There is no binding context for ζ in ξ_i , because since ξ_i is part of ξ , if there is a binding context for ζ in ξ_i , then there is also a (the same) binding context for ζ in ξ ; this would imply that ζ is not a free column reference in ξ , which is against the hypothesis.

Since there is no binding context for ζ in ξ_i , by definition ζ is a free column reference in ξ_i . This means that α has a free column reference in ξ_i , i.e. $\alpha \in FCN(\xi_i)$. Then, $\alpha \in FCN(\xi_1) \cup \dots \cup FCN(\xi_k)$. Q.E.D.

Lemma A.2 If $st \in PTS$, $g \in G$, and for every $i \in \{1, 2, 3, \dots, n\}$, $\tau_i \in TERMS$, $v_i \in D$, and (A.1) – (A.2) hold, then (A.3) also holds.

$$(A.1) \quad \text{If } \tau_i \in VARS, \text{ then } g(\tau_i) = f_D(v_i)$$

$$(A.2) \quad \text{If } \tau_i \in CONS, \text{ then } v_i = h_{cons}(st)(\tau_i)$$

$$(A.3) \quad \|\tau_i\|^{M(st),g} = f_D(v_i),$$

Proof: Since $TERMS = CONS \cup VARS$, $\tau_i \in CONS$ or $\tau_i \in VARS$:

- $\tau_i \in CONS$: By the definition of f_{cons} in section 5.8, (A.4) holds. (A.2) and (A.4) imply (A.5).

$$(A.4) \quad f_{cons}(st)(\tau_i) = f_D(h_{cons}(st)(\tau_i))$$

$$(A.5) \quad f_{cons}(st)(\tau_i) = f_D(v_i)$$

The semantics of TOP imply that $f_{cons}(st)(\tau_i) = \|\tau_i\|^{M(st),g}$. Hence, $\|\tau_i\|^{M(st),g} = f_D(v_i)$.

- $\tau_i \in VARS$: By the semantics of TOP and (A.1), $\|\tau_i\|^{M(st),g} = g(\tau_i) = f_D(v_i)$.

Hence, in both cases $\|\tau_i\|^{M(st),g} = f_D(v_i)$. Q.E.D.

Lemma A.3 If $st \in PTS$, $g \in G$, $g' \in G$, $\phi \in YNFORMS$, $\langle \tau_1, \tau_2, \tau_3, \dots, \tau_n \rangle = \lceil \phi \rceil$, $v_1, v_2, v_3, \dots, v_n \in D$, (A.6) holds, and for every variable β of ϕ , $g(\beta) = g'(\beta)$, then (A.7) also holds.

$$(A.6) \quad \|\tau_1\|^{M(st),g'} = f_D(v_1), \dots, \|\tau_n\|^{M(st),g'} = f_D(v_n)$$

$$(A.7) \quad \|\tau_1\|^{M(st),g} = f_D(v_1), \dots, \|\tau_n\|^{M(st),g} = f_D(v_n)$$

Proof: The definition of $\lceil \phi \rceil$ implies that for every $i \in \{1, 2, 3, \dots, n\}$, $\tau_i \in \text{TERMS}$. Hence, $\tau_i \in \text{CONS}$ or $\tau_i \in \text{VARS}$:

- $\tau_i \in \text{CONS}$: The semantics of TOP implies that $\|\tau_i\|^{M(st),g} = f_{cons}(st)(\tau_i) = \|\tau_i\|^{M(st),g'}$.
- $\tau_i \in \text{VARS}$: By the definition of $\lceil \phi \rceil$, τ_i is a variable in ϕ . Then, $g(\tau_i) = g'(\tau_i)$, because g and g' assign the same values to all the variables of ϕ . τ_i . The semantics of TOP imply that $\|\tau_i\|^{M(st),g} = g(\tau_i)$ and $\|\tau_i\|^{M(st),g'} = g'(\tau_i)$. Then, since $g(\tau_i) = g'(\tau_i)$, $\|\tau_i\|^{M(st),g} = \|\tau_i\|^{M(st),g'}$.

Hence, for every $i \in \{1, 2, 3, \dots, n\}$, $\|\tau_i\|^{M(st),g} = \|\tau_i\|^{M(st),g'}$. This conclusion and (A.6) imply (A.7). Q.E.D.

Lemma A.4 If $g, g' \in G$, $\phi \in \text{YNFORMS}$, $\lceil \phi \rceil = \langle \tau_1, \dots, \tau_n \rangle$, and (A.8) holds, then for every variable β of ϕ , $g(\beta) = g'(\beta)$.

$$(A.8) \quad \|\tau_1\|^{M(st),g} = \|\tau_1\|^{M(st),g'}, \dots, \|\tau_n\|^{M(st),g} = \|\tau_n\|^{M(st),g'}$$

Proof:

From the definition of $\lceil \phi \rceil$, for any variable β of ϕ , there is an $i \in \{1, 2, 3, \dots, n\}$, such that $\tau_i = \beta$. According to the semantics of TOP:

$$(A.9) \quad \|\tau_i\|^{M(st),g} = g(\tau_i)$$

$$(A.10) \quad \|\tau_i\|^{M(st),g'} = g'(\tau_i)$$

(A.8), (A.9), and (A.10) imply that $g(\tau_i) = g'(\tau_i)$, i.e. $g(\beta) = g'(\beta)$. In other words, for every variable β of ϕ , g and g' assign the same value to β . Q.E.D.

Lemma A.5 If $\tau_1, \tau_2, \tau_3, \dots, \tau_n \in \text{TERMS}$, $v_1, v_2, v_3, \dots, v_n \in D$, (A.11) holds, and the mapping $g : \text{VARS} \mapsto \text{OBJS}$ is as in (A.12) (o is a particular element of OBJS , chosen arbitrarily), then $g \in G$.

$$(A.11) \quad \begin{aligned} &\text{if } i, j \in \{1, 2, 3, \dots, n\}, i \neq j, \tau_i = \tau_j, \\ &\text{and } \tau_i, \tau_j \in \text{VARS}, \text{ then } v_i = v_j \end{aligned}$$

$$(A.12) \quad g(\beta) \stackrel{def}{=} \begin{cases} f_D(v_i), & \text{if for some } i \in \{1, 2, 3, \dots, n\}, \beta = \tau_i \\ o, & \text{otherwise} \end{cases}$$

Proof: g is a function. To show this, I need to prove that for each $\beta \in \text{VARS}$, $g(\beta)$ is uniquely defined. There is only one case where $g(\beta)$ may not be uniquely defined: there may be two different $i_1, i_2 \in \{1, 2, 3, \dots, n\}$, with $\beta = \tau_{i_1} = \tau_{i_2}$. In this case I need to show that $f_D(v_{i_1}) = f_D(v_{i_2})$. I will show that $v_{i_1} = v_{i_2}$, which implies $f_D(v_{i_1}) = f_D(v_{i_2})$. The proof follows:

If $i_1, i_2 \in \{1, 2, 3, \dots, n\}$, with $\beta = \tau_{i_1} = \tau_{i_2} \in \text{VARS}$, and $i_1 \neq i_2$, then let i be the smaller of i_1 and i_2 , and j the greater of i_1 and i_2 . By (A.11), $v_i = v_j$. This implies that $v_{i_1} = v_{i_2}$. Hence, $g(\beta)$ is uniquely defined, and g is a function. Since g also maps from VARS to OBJS , $g \in G$. Q.E.D.

Lemma A.6 If $\tau_1^1, \tau_2^1, \dots, \tau_{n_1}^1, \tau_1^2, \dots, \tau_{n_2}^2 \in TERMS$, $v_1^1, v_2^1, \dots, v_{n_1}^1, v_1^2, \dots, v_{n_2}^2 \in D$, $st \in PTS$, $g_1, g_2 \in G$, (A.13) – (A.15) hold, and the mapping $g : VARS \mapsto OBJS$ is as in (A.16) (o is a particular element of $OBJS$, chosen arbitrarily), then $g \in G$.

$$(A.13) \quad \text{if } i \in \{1, 2, 3, \dots, n_1\}, j \in \{1, 2, 3, \dots, n_2\}, \tau_i^1, \tau_j^2 \in VARS, \\ \text{and } \tau_i^1 = \tau_j^2, \text{ then } v_i^1 = v_j^2$$

$$(A.14) \quad \|\tau_1^1\|^{M(st), g_1} = f_D(v_1^1), \dots, \|\tau_{n_1}^1\|^{M(st), g_1} = f_D(v_{n_1}^1)$$

$$(A.15) \quad \|\tau_1^2\|^{M(st), g_2} = f_D(v_1^2), \dots, \|\tau_{n_2}^2\|^{M(st), g_2} = f_D(v_{n_2}^2)$$

$$(A.16) \quad g(\beta) \stackrel{def}{=} \begin{cases} g_1(\beta), & \text{if for some } i \in \{1, 2, 3, \dots, n_1\}, \beta = \tau_i^1 \\ g_2(\beta), & \text{if for some } j \in \{1, 2, 3, \dots, n_2\}, \beta = \tau_j^2 \\ o, & \text{otherwise} \end{cases}$$

Proof: g is a function. To show this, I need to prove that for each $\beta \in VARS$, $g(\beta)$ is uniquely defined. There is only one case where $g(\beta)$ may not be uniquely defined: there may be both an $i \in \{1, 2, 3, \dots, n_1\}$ and a $j \in \{1, 2, 3, \dots, n_2\}$, with $\beta = \tau_i^1 = \tau_j^2 \in VARS$. In this case, I need to prove that $g_1(\beta) = g_2(\beta)$, i.e. that $g_1(\tau_i^1) = g_2(\tau_j^2)$. ($g_1(\tau_i^1)$ and $g_2(\tau_j^2)$ are uniquely defined, because $g_1, g_2 \in G$, which implies that g_1, g_2 are functions.)

Let us assume that $i \in \{1, 2, 3, \dots, n_1\}$, $j \in \{1, 2, 3, \dots, n_2\}$, and that $\beta = \tau_i^1 = \tau_j^2 \in VARS$. Since $\tau_i^1, \tau_j^2 \in VARS$, the semantics of TOP implies that:

$$(A.17) \quad g_1(\tau_i^1) = \|\tau_i^1\|^{M(st), g_1}$$

$$(A.18) \quad g_2(\tau_j^2) = \|\tau_j^2\|^{M(st), g_2}$$

(A.17) and (A.14) imply (A.19), while (A.18) and (A.15) imply (A.20).

$$(A.19) \quad g_1(\tau_i^1) = f_D(v_i^1)$$

$$(A.20) \quad g_2(\tau_j^2) = f_D(v_j^2)$$

Since $i \in \{1, 2, 3, \dots, n_1\}$, $j \in \{1, 2, 3, \dots, n_2\}$, $\tau_i^1, \tau_j^2 \in VARS$, and $\tau_i^1 = \tau_j^2$, (A.13) implies that $v_i^1 = v_j^2$. This, along with (A.19) and (A.20) imply that $g_1(\tau_i^1) = g_2(\tau_j^2)$. Hence, $g(\beta)$ is uniquely defined, and g is a function. Since g also maps from $VARS$ to $OBJS$, $g \in G$. Q.E.D.

Lemma A.7 If $v \in D_P$, $\beta \in VARS$, $g' \in G$, and $g = (g')_{f_D(v)}^\beta$, then $g \in G$.

Proof: To show that $g \in G$, it is enough to show that $f_D(v) \in OBJS$. $f_D(v) \in PERIODS$, because $v \in D_P$. Since $PERIODS \subseteq OBJS$ (sections 3.4 and 5.8), $f_D(v) \in OBJS$. Hence, $g \in G$. Q.E.D.

A.3 Translation rules for yes/no formulae and proof of theorem 5.2

A.3.1 $\pi(\tau_1, \dots, \tau_n)$ **Translation rule**

If $\pi \in PFUNS$, $\tau_1, \dots, \tau_n \in TERMS$, and λ is a TSQL2 value expression, then:

$$\begin{aligned} trans(\pi(\tau_1, \dots, \tau_n), \lambda) &\stackrel{def}{=} \\ &(\text{SELECT DISTINCT } \alpha.1, \alpha.2, \dots, \alpha.n \\ &\quad \text{VALID VALID}(\alpha) \\ &\quad \text{FROM } (h'_{pfuns}(\pi, n)) (\text{SUBPERIOD}) \text{ AS } \alpha \\ &\quad \text{WHERE } \dots \\ &\quad \text{AND } \dots \\ &\quad \vdots \\ &\quad \text{AND } \dots \\ &\quad \text{AND } \lambda \text{ CONTAINS VALID}(\alpha)) \end{aligned}$$

Each time the translation rule is used, α is a new correlation name, obtained by calling the correlation names generator after λ has been supplied. The “...”s in the WHERE clause correspond to all the strings in $S_1 \cup S_2$, where:

$$\begin{aligned} S_1 &= \{“\alpha.i = h'_{cons}(\tau_i)” \mid i \in \{1, 2, 3, \dots, n\} \text{ and } \tau_i \in CONS\} \\ S_2 &= \{“\alpha.i = \alpha.j” \mid i, j \in \{1, 2, 3, \dots, n\}, i < j, \tau_i = \tau_j, \text{ and } \tau_i, \tau_j \in VARS\} \end{aligned}$$

Proof that theorem 5.2 holds for $\phi = \pi(\tau_1, \dots, \tau_n)$

I assume that $\pi \in PFUNS$ and $\tau_1, \dots, \tau_n \in TERMS$. By the syntax of TOP, this implies that $\pi(\tau_1, \dots, \tau_n) \in YNFORMS$. I also assume that $st \in PTS$, λ is a TSQL2 value expression, $g^{db} \in G^{db}$, $eval(st, \lambda, g^{db}) \in D_P^*$, and $\Sigma = trans(\pi(\tau_1, \dots, \tau_n), \lambda)$. By the definition of $\lceil \dots \rceil$, $\lceil \pi(\tau_1, \dots, \tau_n) \rceil = \langle \tau_1, \dots, \tau_n \rangle$. I need to show that the three clauses of theorem 5.2 hold.

Proof of clause 1

The $\alpha.1, \alpha.2, \dots, \alpha.n$ in the SELECT clause of Σ and the $VALID(\alpha)$ in the VALID and WHERE clauses are not free column references in Σ , because Σ is a binding context for all of them. For the same reason, any column references of the form $\alpha.i$ and $\alpha.j$ (deriving from S_1 and S_2) in the WHERE clause are not free column references in Σ . The only remaining parts of Σ where column references (and hence free column references) may occur are the $h'_{pfuns}(\pi, n)$ of the FROM clause, the λ of the WHERE clause, and the $h'_{cons}(\tau_{i_1}), h'_{cons}(\tau_{i_2}), h'_{cons}(\tau_{i_3}), \dots, h'_{cons}(\tau_{i_m})$ of the WHERE clause ($h'_{cons}(\tau_{i_1}), \dots, h'_{cons}(\tau_{i_m})$ derive from S_1 ; $\tau_{i_1}, \dots, \tau_{i_m}$ are all the TOP constants among τ_1, \dots, τ_n). By lemma A.1, this implies that:

$$\begin{aligned} (A.21) \quad FCN(\Sigma) &\subseteq FCN(h'_{pfuns}(\pi, n)) \cup FCN(\lambda) \cup \\ &\quad FCN(h'_{cons}(\tau_{i_1})) \cup \dots \cup FCN(h'_{cons}(\tau_{i_m})) \end{aligned}$$

According to section 5.9, for every $\kappa \in CONS$, $FCN(h'_{cons}(\kappa)) = \emptyset$. Since $\tau_{i_1}, \dots, \tau_{i_m} \in CONS$ (see comments above), $FCN(h'_{cons}(\tau_{i_1})) = \emptyset, \dots, FCN(h'_{cons}(\tau_{i_m})) = \emptyset$. Ac-

cording to section 5.9, it is also true that for every $\pi \in PFUNS$ and $n \in \{1, 2, 3, \dots\}$, $FCN(h'_{pfuns}(\pi, n)) = \emptyset$. Hence, (A.21) becomes $FCN(\Sigma) \subseteq FCN(\lambda)$. Clause 1 has been proven.

Proof of clause 2

According to section 5.9, $h'_{pfuns}(\pi, n)$ is a TSQL2 SELECT statement, $FCN(h'_{pfuns}(\pi, n)) = \emptyset$, and $eval(st, h'_{pfuns}(\pi, n)) \in NVREL_P(n)$. The α of Σ ranges over the tuples of the relation $subperiod(eval(st, h'_{pfuns}(\pi, n)))$. From the definition of *subperiod* (section 5.3.2), it is easy to see that $subperiod(eval(st, h'_{pfuns}(\pi, n)))$ is a valid-time relation that has the same number of explicit attributes as $eval(st, h'_{pfuns}(\pi, n))$, i.e. n . Hence, α ranges over tuples $\langle v_1, \dots, v_n; v_t \rangle \in subperiod(eval(st, h'_{pfuns}(\pi, n)))$.

The α of Σ is generated by calling the correlation names generator after λ has been supplied. Hence, α cannot appear in λ . Since α does not appear in λ , for every tuple $\langle v_1, \dots, v_n; v_t \rangle$:

$$(A.22) \quad eval(st, \lambda, (g^{db})_{\langle v_1, \dots, v_n; v_t \rangle}^\alpha) = eval(st, \lambda, g^{db})$$

The reader should now be able to see from the translation rule that (A.23) holds. Intuitively, $\langle v_1, \dots, v_n; v_t \rangle$ is the tuple of $subperiod(eval(st, h'_{pfuns}(\pi, n)))$ to which α refers. The last line of (A.23) corresponds to the CONTAINS constraint in the WHERE clause of Σ . I should have used $eval(st, \lambda, (g^{db})_{\langle v_1, \dots, v_n; v_t \rangle}^\alpha)$ instead of $eval(st, \lambda, g^{db})$, to capture the fact that if there is any free column reference of α in λ , this has to be taken to refer to the $\langle v_1, \dots, v_n; v_t \rangle$ tuple to which α refers. By (A.22), however, $eval(st, \lambda, (g^{db})_{\langle v_1, \dots, v_n; v_t \rangle}^\alpha)$ is the same as $eval(st, \lambda, g^{db})$. The second and third lines of (A.23) correspond to the restrictions of S_1 and S_2 (see also the comments about the equality predicate in section 5.3.6). I do not include in the arguments of $eval(st, h'_{cons}(\tau_i))$ the assignment to the correlation names, because according to section 5.9, for $\tau_i \in CONS$, $FCN(h'_{cons}(\tau_i)) = \emptyset$.

$$(A.23) \quad eval(st, \Sigma, g^{db}) = \{ \langle v_1, \dots, v_n; v_t \rangle \in subperiod(eval(st, h'_{pfuns}(\pi, n))) \mid \\ \text{if } i \in \{1, 2, 3, \dots, n\} \text{ and } \tau_i \in CONS, \text{ then } v_i = eval(st, h'_{cons}(\tau_i)), \\ \text{if } i, j \in \{1, 2, 3, \dots, n\}, i < j, \tau_i = \tau_j, \text{ and } \tau_i, \tau_j \in VARS, \text{ then } v_i = v_j, \\ f_D(v_t) \subseteq f_D(eval(st, \lambda, g^{db})) \}$$

According to the definition of *subperiod* (section 5.3.2), (A.24) holds iff (A.25) holds for some v'_t . By the definition of h'_{pfuns} of section 5.9, (A.25) is in turn equivalent to (A.26).

$$(A.24) \quad \langle v_1, \dots, v_n; v_t \rangle \in subperiod(eval(st, h'_{pfuns}(\pi, n)))$$

$$(A.25) \quad \langle v_1, \dots, v_n; v'_t \rangle \in eval(st, h'_{pfuns}(\pi, n)) \text{ and } f_D(v_t) \sqsubseteq f_D(v'_t)$$

$$(A.26) \quad \langle v_1, \dots, v_n; v'_t \rangle \in h'_{pfuns}(st)(\pi, n) \text{ and } f_D(v_t) \sqsubseteq f_D(v'_t)$$

Using the fact that (A.24) holds iff (A.26) holds for some v'_t , and the fact that for

$\tau_i \in CONS$, $eval(st, h'_{cons}(\tau_i)) = h_{cons}(st)(\tau_i)$ (section 5.9), (A.23) becomes:

$$(A.27) \quad eval(st, \Sigma, g^{db}) = \{ \langle v_1, \dots, v_n; v_t \rangle \mid \text{for some } v'_t, \\ \langle v_1, \dots, v_n; v'_t \rangle \in h_{pfuns}(st)(\pi, n), f_D(v_t) \sqsubseteq f_D(v'_t) \\ \text{if } i \in \{1, 2, 3, \dots, n\} \text{ and } \tau_i \in CONS, \text{ then } v_i = h_{cons}(st)(\tau_i), \\ \text{if } i, j \in \{1, 2, 3, \dots, n\}, i < j, \tau_i = \tau_j, \text{ and } \tau_i, \tau_j \in VARS, \text{ then } v_i = v_j, \\ f_D(v_t) \subseteq f_D(eval(st, \lambda, g^{db})) \}$$

For every $\langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$, the $f_D(v_t) \sqsubseteq f_D(v'_t)$ in the second line of (A.27) implies that $f_D(v_t) \in PERIODS$, which in turn implies that $v_t \in D_P$. That is, all the time-stamps of $eval(st, \Sigma, g^{db})$ are elements of D_P . (A.27) also implies that $eval(st, \Sigma, g^{db})$ is a valid-time relation of n explicit attributes. Hence, $eval(st, \Sigma, g^{db}) \in VREL_P(n)$, and clause 2 has been proven.

Proof of clause 3

Using the definition of $\|\pi(\tau_1, \dots, \tau_n)\|^{M(st), st, et, lt, g}$ (section 3.6), clause 3 becomes:

$$(A.28) \quad \langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db}) \text{ iff for some } g \text{ and } p_{mxl}: \\ g \in G \\ (A.29) \quad \|\tau_1\|^{M(st), g} = f_D(v_1), \dots, \|\tau_n\|^{M(st), g} = f_D(v_n) \\ (A.30) \quad p_{mxl} \in f_{pfuns}(st)(\pi, n)(\|\tau_1\|^{M(st), g}, \dots, \|\tau_n\|^{M(st), g}) \\ (A.31) \quad f_D(v_t) \sqsubseteq p_{mxl} \\ (A.32) \quad f_D(v_t) \sqsubseteq f_D(eval(st, \lambda, g^{db}))$$

I first show that the forward direction of clause 3 holds. I assume that $\langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$. Then, (A.27) implies that for some v'_t :

$$(A.33) \quad \langle v_1, \dots, v_n; v'_t \rangle \in h_{pfuns}(st)(\pi, n) \\ (A.34) \quad f_D(v_t) \sqsubseteq f_D(v'_t) \\ (A.35) \quad \text{if } i \in \{1, 2, 3, \dots, n\}, \text{ and } \tau_i \in CONS, \text{ then } v_i = h_{cons}(st)(\tau_i) \\ (A.36) \quad \text{if } i, j \in \{1, 2, 3, \dots, n\}, i < j, \tau_i = \tau_j, \text{ and } \tau_i, \tau_j \in VARS, \text{ then } v_i = v_j \\ (A.37) \quad f_D(v_t) \subseteq f_D(eval(st, \lambda, g^{db}))$$

To prove the forward direction of clause 3, I must prove that for some g and p_{mxl} , (A.28) – (A.32) hold. I define the mapping $g : VARS \mapsto OBJS$ as follows:

$$g(\beta) \stackrel{def}{=} \begin{cases} f_D(v_i), & \text{if for some } i \in \{1, 2, 3, \dots, n\}, \beta = \tau_i \\ o, & \text{otherwise} \end{cases}$$

where o is a particular element of $OBJS$, chosen arbitrarily. (A.28) follows from lemma A.5, the definition of g , and (A.36). I set p_{mxl} as in (A.38), and show that (A.29) – (A.32) also hold. (A.29) follows from lemma A.2, (A.35), and the definition of g .

$$(A.38) \quad p_{mxl} = f_D(v'_t)$$

I now prove (A.30). (A.29) (proven above) implies (A.39). (A.33) and (A.39) imply (A.40). (A.40) and the definition of f_{pfun} of section 5.8 imply (A.41). (A.41) and (A.38) imply (A.30).

$$(A.39) \quad v_1 = f_D^{-1}(\|\tau_1\|^{M(st),g}), \dots, v_n = f_D^{-1}(\|\tau_n\|^{M(st),g})$$

$$(A.40) \quad \langle f_D^{-1}(\|\tau_1\|^{M(st),g}), \dots, f_D^{-1}(\|\tau_n\|^{M(st),g}); v'_t \rangle \in h_{pfun}(st)(\pi, n)$$

$$(A.41) \quad f_D(v'_t) \in f_{pfun}(st)(\pi, n)(\|\tau_1\|^{M(st),g}, \dots, \|\tau_n\|^{M(st),g})$$

(A.31) follows from (A.34) and (A.38). I now prove (A.32). (A.34) implies that $f_D(v_t) \in PERIODS$. From the hypothesis, $eval(st, \lambda, g^{db}) \in D_P^*$, which implies that $f_D(eval(st, \lambda, g^{db}))$ is a period or the empty set. $f_D(eval(st, \lambda, g^{db}))$ cannot be the empty set, because according to (A.37) $f_D(v_t)$ (which is a period and therefore a non-empty set) is a subset of $f_D(eval(st, \lambda, g^{db}))$. Hence, $f_D(eval(st, \lambda, g^{db})) \in PERIODS$. (A.37) and the fact that both $f_D(v_t)$ and $f_D(eval(st, \lambda, g^{db}))$ are periods imply (A.32). The forward direction of clause 3 has been proven.

I now prove the backwards direction of clause 3. I assume that (A.28) – (A.32) hold for some g and p_{mxl} . I need to show that $\langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$. According to (A.27), it is enough to prove that for some v'_t , (A.33) – (A.37) hold. I set $v'_t = f_D^{-1}(p_{mxl})$, which implies (A.42).

$$(A.42) \quad p_{mxl} = f_D(v'_t)$$

I first prove (A.33). (A.30), (A.42), and the definition of f_{pfun} of section 5.8 imply (A.43). (A.29) implies (A.44). (A.43) and (A.44) imply (A.33).

$$(A.43) \quad \langle f_D^{-1}(\|\tau_1\|^{M(st),g}), \dots, f_D^{-1}(\|\tau_n\|^{M(st),g}); v'_t \rangle \in h_{pfun}(st)(\pi, n)$$

$$(A.44) \quad f_D^{-1}(\|\tau_1\|^{M(st),g}) = v_1, \dots, f_D^{-1}(\|\tau_n\|^{M(st),g}) = v_n$$

(A.34) follows from (A.31) and (A.42). I now prove (A.35). If $i \in \{1, 2, 3, \dots, n\}$ and $\tau_i \in CONS$, the semantics of TOP implies (A.45), and (A.29) implies (A.46).

$$(A.45) \quad \|\tau_i\|^{M(st),g} = f_{cons}(st)(\tau_i)$$

$$(A.46) \quad \|\tau_i\|^{M(st),g} = f_D(v_i)$$

(A.45) and (A.46) imply that $f_D(v_i) = f_{cons}(st)(\tau_i)$, which in turn implies (A.47). The definition of f_{cons} of section 5.8 implies (A.48). (A.47) and (A.48) imply that $v_i = h_{cons}(st)(\tau_i)$. (A.35) has been proven.

$$(A.47) \quad v_i = f_D^{-1}(f_{cons}(st)(\tau_i))$$

$$(A.48) \quad f_{cons}(st)(\tau_i) = f_D(h_{cons}(st)(\tau_i))$$

I now prove (A.36). If $i, j \in \{1, 2, 3, \dots, n\}$ and $\tau_i = \tau_j$, then $\|\tau_i\|^{M(st),g} = \|\tau_j\|^{M(st),g}$. Then, (A.29) implies that $f_D(v_i) = f_D(v_j)$, which in turn implies that $f_D^{-1}(f_D(v_i)) = f_D^{-1}(f_D(v_j))$, i.e. $v_i = v_j$. (A.36) has been proven. (A.37) follows from (A.32). The backwards direction of clause 3 has been proven.

A.3.2 $Culm[\pi(\tau_1, \dots, \tau_n)]$ **Translation rule**

If $\pi \in PFUNS$, $\tau_1, \dots, \tau_n \in TERMS$, and λ is a TSQL2 value expression, then:

$$\begin{aligned} trans(Culm[\pi(\tau_1, \dots, \tau_n)], \lambda) &\stackrel{def}{=} \\ &(\text{SELECT DISTINCT } \alpha_1.1, \alpha_1.2, \dots, \alpha_1.n \\ &\quad \text{VALID PERIOD}(\text{BEGIN}(\text{VALID}(\alpha_1)), \text{END}(\text{VALID}(\alpha_1))) \\ &\quad \text{FROM } (h'_{pfuns}(\pi, n))(\text{ELEMENT}) \text{ AS } \alpha_1, \\ &\quad \quad (h'_{culms}(\pi, n)) \text{ AS } \alpha_2 \\ &\quad \text{WHERE } \alpha_1.1 = \alpha_2.1 \\ &\quad \quad \text{AND } \alpha_1.2 = \alpha_2.2 \\ &\quad \quad \vdots \\ &\quad \text{AND } \alpha_1.n = \alpha_2.n \\ &\quad \text{AND } \dots \\ &\quad \quad \vdots \\ &\quad \text{AND } \dots \\ &\quad \text{AND } \lambda \text{ CONTAINS PERIOD}(\text{BEGIN}(\text{VALID}(\alpha_1)), \text{END}(\text{VALID}(\alpha_1))) \end{aligned}$$

Each time the translation rule is used, α_1 and α_2 are two new different correlation names, obtained by calling the correlation names generator after λ has been supplied. The “...”s in the WHERE clause correspond to all the strings in $S_1 \cup S_2$, where S_1 and S_2 are as in section A.3.1, except that α is now α_1 .

Proof that theorem 5.2 holds for $\phi = Culm[\pi(\tau_1, \dots, \tau_n)]$

I assume that $\pi \in PFUNS$ and $\tau_1, \dots, \tau_n \in TERMS$. By the syntax of TOP, this implies that $Culm[\pi(\tau_1, \dots, \tau_n)] \in YNFORMS$. I also assume that $st \in PTS$, that λ is a TSQL2 value expression, $g^{db} \in G^{db}$, $eval(st, \lambda, g^{db}) \in D_P^*$, and that $\Sigma = trans(Culm[\pi(\tau_1, \dots, \tau_n)], \lambda)$. By the definition of $\lceil \dots \rceil$, $\lceil Culm[\pi(\tau_1, \dots, \tau_n)] \rceil = \langle \tau_1, \dots, \tau_n \rangle$. I need to show that the three clauses of theorem 5.2 hold.

Proof of clause 1

The $\alpha_1.1, \alpha_1.2, \dots, \alpha_1.n$ in the SELECT clause of Σ , and the four $\text{VALID}(\alpha_1)$ in the VALID and WHERE clauses are not free column references in Σ , because Σ is a binding context for all of them. For the same reason, all the column references of the form $\alpha.i$ ($i \in \{1, 2, 3, \dots, n\}$) in the WHERE clause of Σ are not free column references in Σ . The only remaining parts of Σ where column references (and hence free column references) may occur are the $h'_{pfuns}(\pi, n)$ and the $h'_{culms}(\pi, n)$ of the FROM clause, the λ of the WHERE clause, and the $h'_{cons}(\tau_{i_1}), h'_{cons}(\tau_{i_2}), h'_{cons}(\tau_{i_3}), \dots, h'_{cons}(\tau_{i_m})$ of the WHERE clause ($h'_{cons}(\tau_{i_1}), \dots, h'_{cons}(\tau_{i_m})$ derive from S_1 ; $\tau_{i_1}, \dots, \tau_{i_m}$ are all the TOP constants among τ_1, \dots, τ_n). By lemma A.1, this implies that:

$$\begin{aligned} (A.49) \quad FCN(\Sigma) &\subseteq FCN(h'_{pfuns}(\pi, n)) \cup FCN(h'_{culms}(\pi, n)) \cup \\ &\quad FCN(\lambda) \cup FCN(h'_{cons}(\tau_{i_1})) \cup \dots \cup FCN(h'_{cons}(\tau_{i_m})) \end{aligned}$$

By section 5.9, for every $\kappa \in CONS$, $FCN(h'_{cons}(\kappa)) = \emptyset$. Since $\tau_{i_1}, \dots, \tau_{i_m} \in CONS$ (see comments above), $FCN(h'_{cons}(\tau_{i_1})) = \emptyset, \dots, FCN(h'_{cons}(\tau_{i_m})) = \emptyset$. According to section 5.9, it is also true that for every $\pi \in PFUNS$ and $n \in \{1, 2, 3, \dots\}$, $FCN(h'_{pfuns}(\pi, n)) = \emptyset$ and $FCN(h'_{culms}(\pi, n)) = \emptyset$. Hence, (A.49) becomes $FCN(\Sigma) \subseteq FCN(\lambda)$. Clause 1 has been proven.

Proof of clause 2

According to section 5.9, $h'_{pfuns}(\pi, n)$ and $h'_{culms}(\pi, n)$ are TSQL2 **SELECT** statements, $FCN(h'_{pfuns}(\pi, n)) = FCN(h'_{culms}(\pi, n)) = \emptyset$, $eval(st, h'_{pfuns}(\pi, n)) \in NVREL_P(n)$, and $eval(st, h'_{culms}(\pi, n)) \in SREL(n)$. The α_1 of Σ ranges over the tuples of the relation $coalesce(eval(st, h'_{pfuns}(\pi, n)))$ (see section 5.2.4). From the definition of *coalesce*, it is easy to see that $coalesce(eval(st, h'_{pfuns}(\pi, n)))$ is a valid-time relation that has the same number of explicit attributes as $eval(st, h'_{pfuns}(\pi, n))$, i.e. n . Hence, α_1 ranges over tuples $\langle v_1, \dots, v_n; v'_t \rangle \in coalesce(eval(st, h'_{pfuns}(\pi, n)))$. The α_2 of Σ ranges over the tuples of $eval(st, h'_{culms}(\pi, n))$. Since $eval(st, h'_{culms}(\pi, n)) \in SREL(n)$, α_2 ranges over tuples $\langle v_1, \dots, v_n \rangle \in eval(st, h'_{culms}(\pi, n))$.

The α_1 and α_2 of Σ are generated by calling the correlation names generator after λ has been supplied. Hence, α_1 and α_2 cannot appear in λ . The fact that α_1 and α_2 do not appear in λ means that for every $v_1, \dots, v_n \in D$ and every $v'_t \in D_T$:

$$(A.50) \quad eval(st, \lambda, ((g^{db})^{\alpha_1}_{\langle v_1, \dots, v_n; v'_t \rangle})^{\alpha_2}_{\langle v_1, \dots, v_n \rangle}) = eval(st, \lambda, g^{db})$$

The reader should now be able to see from the translation rule that (A.51) holds. Intuitively, $\langle v_1, \dots, v_n; v'_t \rangle$ is the tuple of $coalesce(eval(st, h'_{pfuns}(\pi, n)))$ to which α_1 refers, and $\langle v_1, \dots, v_n \rangle$ is the tuple of $eval(st, h'_{culms}(\pi, n))$ to which α_2 refers. The last line of (A.51) corresponds to the **CONTAINS** constraint in the **WHERE** clause of Σ . I should have used $eval(st, \lambda, ((g^{db})^{\alpha_1}_{\langle v_1, \dots, v_n; v'_t \rangle})^{\alpha_2}_{\langle v_1, \dots, v_n \rangle})$ instead of $eval(st, \lambda, g^{db})$, to capture the fact that if there are any free column references of α_1 or α_2 in λ , these have to be taken to refer to the $\langle v_1, \dots, v_n; v'_t \rangle$ or $\langle v_1, \dots, v_n \rangle$ tuples to which α_1 and α_2 refer respectively. By (A.50), however, $eval(st, \lambda, ((g^{db})^{\alpha_1}_{\langle v_1, \dots, v_n; v'_t \rangle})^{\alpha_2}_{\langle v_1, \dots, v_n \rangle})$ is the same as $eval(st, \lambda, g^{db})$. The fifth and sixth lines of (A.51) correspond to the restrictions of S_1 and S_2 (see also the comments about the equality predicate in section 5.3.6). I do not include in the arguments of $eval(st, h'_{cons}(\tau_i))$ the assignment to the correlation names, because according to section 5.9, for $\tau_i \in CONS$, $FCN(h'_{cons}(\tau_i)) = \emptyset$.

$$(A.51) \quad eval(st, \Sigma, g^{db}) = \{ \langle v_1, \dots, v_n; v'_t \rangle \mid \text{for some } v'_t, \\ \langle v_1, \dots, v_n; v'_t \rangle \in coalesce(eval(st, h'_{pfuns}(\pi, n))), \\ \langle v_1, \dots, v_n \rangle \in eval(st, h'_{culms}(\pi, n)), \\ f_D(v_t) = [minpt(f_D(v'_t)), maxpt(f_D(v'_t))], \\ \text{if } i \in \{1, 2, 3, \dots, n\} \text{ and } \tau_i \in CONS, \text{ then } v_i = eval(st, h'_{cons}(\tau_i)), \\ \text{if } i, j \in \{1, 2, 3, \dots, n\}, i < j, \tau_i = \tau_j, \text{ and } \tau_i, \tau_j \in VARS, \text{ then } v_i = v_j, \\ f_D(v_t) \subseteq f_D(eval(st, \lambda, g^{db})) \}$$

According to section 5.9:

$$(A.52) \quad eval(st, h'_{pfuns}(\pi, n)) = h_{pfuns}(st)(\pi, n)$$

$$(A.53) \quad eval(st, h'_{culms}(\pi, n)) = h_{culms}(st)(\pi, n)$$

$$(A.54) \quad \text{for } \tau_i \in CONS, \quad eval(st, h'_{cons}(\tau_i)) = h_{cons}(st)(\tau_i)$$

Using (A.52), (A.53), (A.54), and the definition of *coalesce* of section 5.2.4, (A.51) becomes:

$$(A.55) \quad \begin{aligned} eval(st, \Sigma, g^{db}) &= \{ \langle v_1, \dots, v_n; v_t \rangle \mid \text{for some } v'_t, v''_t, \\ &\quad \langle v_1, \dots, v_n; v''_t \rangle \in h_{pfuns}(st)(\pi, n), \\ f_D(v'_t) &= \bigcup_{\langle v_1, \dots, v_n; v'''_t \rangle \in h_{pfuns}(st)(\pi, n)} f_D(v'''_t) \\ &\quad \langle v_1, \dots, v_n \rangle \in h_{culms}(st)(\pi, n), \\ f_D(v_t) &= [minpt(f_D(v'_t)), maxpt(f_D(v'_t))], \\ \text{if } i \in \{1, 2, 3, \dots, n\} \text{ and } \tau_i \in CONS, \text{ then } v_i &= h_{cons}(st)(\tau_i), \\ \text{if } i, j \in \{1, 2, 3, \dots, n\}, i < j, \tau_i = \tau_j, \text{ and } \tau_i, \tau_j \in VARS, \text{ then } v_i &= v_j, \\ f_D(v_t) &\subseteq f_D(eval(st, \lambda, g^{db})) \} \end{aligned}$$

According to (A.55), for every tuple $\langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$, there is a v'_t , such that $f_D(v'_t)$ is the union of all the temporal elements $f_D(v'''_t)$ represented by time-stamps of tuples $\langle v_1, \dots, v_n; v'''_t \rangle \in h_{pfuns}(st)(\pi, n)$. ($f_D(v'_t)$ is not the empty set, because by the second line of (A.55), there is at least one tuple $\langle v_1, \dots, v_n; v''_t \rangle \in h_{pfuns}(st)(\pi, n)$). $f_D(v_t)$ is the period $[minpt(f_D(v'_t)), maxpt(f_D(v'_t))]$. This implies that $v_t \in D_P$. We have concluded that for every tuple in $eval(st, \Sigma, g^{db})$, the time-stamp v_t is an element of D_P . (A.55) also implies that $eval(st, \Sigma, g^{db})$ is a valid-time relation of n explicit attributes. Hence, $eval(st, \Sigma, g^{db}) \in VREL_P(n)$. Clause 2 has been proven.

Proof of clause 3

Using the definition of $\|Culm[\pi(\tau_1, \dots, \tau_n)]\|^{M(st), st, et, lt, g}$ (section 3.9), clause 3 becomes:

$$(A.56) \quad \langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db}) \text{ iff for some } g \text{ and } S: \\ g \in G \\ (A.57) \quad \|\tau_1\|^{M(st), g} = f_D(v_1), \dots, \|\tau_n\|^{M(st), g} = f_D(v_n) \\ (A.58) \quad f_D(v_t) \sqsubseteq f_D(eval(st, \lambda, g^{db})) \\ (A.59) \quad f_{culms}(st)(\pi, n)(\|\tau_1\|^{M(st), g}, \dots, \|\tau_n\|^{M(st), g}) = T \\ (A.60) \quad S \neq \emptyset \\ (A.61) \quad f_D(v_t) = [minpt(S), maxpt(S)] \\ (A.62) \quad S = \bigcup_{p \in f_{pfuns}(st)(\pi, n)(\|\tau_1\|^{M(st), g}, \dots, \|\tau_n\|^{M(st), g})} p$$

I first show that the forward direction of clause 3 holds. I assume that $\langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$. I need to show that for some g and S , (A.56) – (A.62) hold. The

assumption that $\langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$ and (A.55) imply that for some v'_t and v''_t :

$$(A.63) \quad \langle v_1, \dots, v_n; v''_t \rangle \in h_{pfuns}(st)(\pi, n)$$

$$(A.64) \quad f_D(v'_t) = \bigcup_{\langle v_1, \dots, v_n; v''_t \rangle \in h_{pfuns}(st)(\pi, n)} f_D(v''_t)$$

$$(A.65) \quad \langle v_1, \dots, v_n \rangle \in h_{culms}(st)(\pi, n)$$

$$(A.66) \quad f_D(v_t) = [minpt(f_D(v'_t)), maxpt(f_D(v'_t))]$$

$$(A.67) \quad \text{if } i \in \{1, 2, 3, \dots, n\} \text{ and } \tau_i \in CONS, \text{ then } v_i = h_{cons}(st)(\tau_i)$$

$$(A.68) \quad \text{if } i, j \in \{1, 2, 3, \dots, n\}, i < j, \tau_i = \tau_j, \text{ and } \tau_i, \tau_j \in VARS, \text{ then } v_i = v_j$$

$$(A.69) \quad f_D(v_t) \subseteq f_D(eval(st, \lambda, g^{db}))$$

I define the mapping $g : VARS \mapsto OBJS$ as follows:

$$g(\beta) \stackrel{def}{=} \begin{cases} f_D(v_i), & \text{if for some } i \in \{1, 2, 3, \dots, n\}, \beta = \tau_i \\ o, & \text{otherwise} \end{cases}$$

where o is a particular element of $OBJS$, chosen arbitrarily. (A.56) follows from lemma A.5, (A.68), and the definition of g . I set S as in (A.70), and show that (A.57) – (A.62) also hold. (A.57) follows from lemma A.2, (A.67), and the definition of g .

$$(A.70) \quad S = f_D(v'_t)$$

I now prove (A.59). (A.57) (proven above) implies (A.71). (A.71) and (A.65) imply (A.72). (A.72) and the definition of f_{culms} of section 5.8 imply (A.59).

$$(A.71) \quad f_D^{-1}(\|\tau_1\|^{M(st),g}) = v_1, \dots, f_D^{-1}(\|\tau_n\|^{M(st),g}) = v_n$$

$$(A.72) \quad \langle f_D^{-1}(\|\tau_1\|^{M(st),g}), \dots, f_D^{-1}(\|\tau_n\|^{M(st),g}) \rangle \in h_{culms}(st)(\pi, n)$$

I now prove (A.60). (A.64) and (A.70) imply (A.73). (A.63) implies that there is at least one tuple $\langle v_1, \dots, v_n; v''_t \rangle$ in $h_{pfuns}(st)(\pi, n)$. Then, by (A.73), S contains at least the chronons of $f_D(v''_t)$, and therefore $S \neq \emptyset$. (A.60) has been proven.

$$(A.73) \quad S = \bigcup_{\langle v_1, \dots, v_n; v''_t \rangle \in h_{pfuns}(st)(\pi, n)} f_D(v''_t)$$

I now prove (A.62). Using (A.71), (A.73) becomes (A.74). By the definition of f_{pfuns} of section 5.8, (A.75) is equivalent to (A.76). Then, (A.74) can be written as (A.77). By replacing $f_D(v''_t)$ with p , (A.77) becomes (A.62).

$$(A.74) \quad S = \bigcup_{\langle f_D^{-1}(\|\tau_1\|^{M(st),g}), \dots, f_D^{-1}(\|\tau_n\|^{M(st),g}); v''_t \rangle \in h_{pfuns}(st)(\pi, n)} f_D(v''_t)$$

$$(A.75) \quad \langle f_D^{-1}(\|\tau_1\|^{M(st),g}), \dots, f_D^{-1}(\|\tau_n\|^{M(st),g}); v''_t \rangle \in h_{pfuns}(st)(\pi, n)$$

$$(A.76) \quad f_D(v''_t) \in f_{pfuns}(\pi, n)(\|\tau_1\|^{M(st),g}, \dots, \|\tau_n\|^{M(st),g})$$

$$(A.77) \quad S = \bigcup_{f_D(v''_t) \in f_{pfuns}(\pi, n)(\|\tau_1\|^{M(st),g}, \dots, \|\tau_n\|^{M(st),g})} f_D(v''_t)$$

(A.61) follows from (A.70) and (A.66). It remains to prove (A.58). (A.60) and (A.61) (both proven above) imply that $f_D(v_t) \in PERIODS$. From the hypothesis, $eval(st, \lambda, g^{db}) \in D_P^*$, which implies that $f_D(eval(st, \lambda, g^{db}))$ is a period or the empty set. $f_D(eval(st, \lambda, g^{db}))$ cannot be the empty set, because according to (A.69) $f_D(v_t)$ (which is a period and therefore a non-empty set) is a subset of $f_D(eval(st, \lambda, g^{db}))$. Hence, $f_D(eval(st, \lambda, g^{db})) \in PERIODS$. (A.69) and the fact that both $f_D(v_t)$ and $f_D(eval(st, \lambda, g^{db}))$ are periods imply (A.58). The forward direction of clause 3 has been proven.

I now prove the backwards direction of clause 3. I assume that (A.56) – (A.62) hold. I need to prove that $\langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$. According to (A.55), it is enough to prove that for some v'_t and v''_t , (A.63) – (A.69) hold. (A.69) follows from (A.58).

I now prove (A.67). If $i \in \{1, 2, 3, \dots, n\}$ and $\tau_i \in CONS$, then the semantics of TOP implies (A.78), and (A.57) implies (A.79).

$$(A.78) \quad \|\tau_i\|^{M(st),g} = f_{cons}(st)(\tau_i)$$

$$(A.79) \quad \|\tau_i\|^{M(st),g} = f_D(v_i)$$

(A.78) and (A.79) imply that $f_D(v_i) = f_{cons}(st)(\tau_i)$, which in turn implies (A.80). The definition of f_{cons} of section 5.8 implies (A.81). (A.80) and (A.81) imply that $v_i = h_{cons}(st)(\tau_i)$. (A.67) has been proven.

$$(A.80) \quad v_i = f_D^{-1}(f_{cons}(st)(\tau_i))$$

$$(A.81) \quad f_{cons}(st)(\tau_i) = f_D(h_{cons}(st)(\tau_i))$$

I now prove (A.68). If $i, j \in \{1, 2, 3, \dots, n\}$ and $\tau_i = \tau_j$, then $\|\tau_i\|^{M(st),g} = \|\tau_j\|^{M(st),g}$. Then, from (A.57), $f_D(v_i) = f_D(v_j)$, which implies that $f_D^{-1}(f_D(v_i)) = f_D^{-1}(f_D(v_j))$, i.e. $v_i = v_j$. (A.68) has been proven.

I now prove (A.65). (A.59) and the definition of f_{culms} of section 5.8 imply (A.82). (A.57) implies (A.83). (A.82) and (A.83) imply (A.65).

$$(A.82) \quad \langle f_D^{-1}(\|\tau_1\|^{M(st),g}), \dots, f_D^{-1}(\|\tau_n\|^{M(st),g}) \rangle \in h_{culms}(st)(\pi, n)$$

$$(A.83) \quad f_D^{-1}(\|\tau_1\|^{M(st),g}) = v_1, \dots, f_D^{-1}(\|\tau_n\|^{M(st),g}) = v_n$$

It remains to prove that (A.63), (A.64), and (A.66) hold for some v'_t, v''_t . I start with (A.63). According to section 5.8, $f_{pfuns}(st)(\pi, n)(\|\tau_1\|^{M(st),g}, \dots, \|\tau_n\|^{M(st),g})$ is a set of periods. By (A.62), S is the union of all these periods. According to (A.60), S is not the empty set, which implies that there is at least one period p' such that:

$$(A.84) \quad p' \in f_{pfuns}(st)(\pi, n)(\|\tau_1\|^{M(st),g}, \dots, \|\tau_n\|^{M(st),g})$$

Let $v''_t = f_D^{-1}(p')$, which implies that $p' = f_D(v''_t)$. Then, from (A.84) we get:

$$(A.85) \quad f_D(v''_t) \in f_{pfuns}(st)(\pi, n)(\|\tau_1\|^{M(st),g}, \dots, \|\tau_n\|^{M(st),g})$$

(A.85) and the definition of f_{pfuns} of section 5.8 imply (A.86). (A.86) and (A.83) imply (A.63).

$$(A.86) \quad \langle f_D^{-1}(\|\tau_1\|^{M(st),g}), \dots, f_D^{-1}(\|\tau_n\|^{M(st),g}); v''_t \rangle \in h_{pfuns}(st)(\pi, n)$$

From the discussion above, S is a (non-empty) union of periods. This implies that S is a temporal element, which in turn implies that there is a $v'_t \in D_T$, such that (A.87) holds. (A.66) follows from (A.61) and (A.87).

$$(A.87) \quad f_D(v'_t) = S$$

I now prove (A.64). (A.62) and (A.87) imply (A.88).

$$(A.88) \quad f_D(v'_t) = \bigcup_{p \in f_{pfun}(st)(\pi, n)(\|\tau_1\|^{M(st),g}, \dots, \|\tau_n\|^{M(st),g})} p$$

According to the discussion above, $f_{pfun}(st)(\pi, n)(\|\tau_1\|^{M(st),g}, \dots, \|\tau_n\|^{M(st),g})$ is a set of periods. Therefore, for every p in that set, there is a $v_t''' \in D_P$, such that $f_D(v_t''') = p$. Hence, (A.88) can be written as (A.89).

$$(A.89) \quad f_D(v'_t) = \bigcup_{f_D(v_t''') \in f_{pfun}(st)(\pi, n)(\|\tau_1\|^{M(st),g}, \dots, \|\tau_n\|^{M(st),g})} f_D(v_t''')$$

By the definition of f_{pfun} of section 5.8, (A.90) is equivalent to (A.91). By (A.83), (A.91) is in turn equivalent to (A.92). (A.89) and the fact that (A.90) is equivalent to (A.92) imply (A.64). The backwards direction of clause 3 has been proven.

$$(A.90) \quad f_D(v_t''') \in f_{pfun}(st)(\pi, n)(\|\tau_1\|^{M(st),g}, \dots, \|\tau_n\|^{M(st),g})$$

$$(A.91) \quad \langle f_D^{-1}(\|\tau_1\|^{M(st),g}), \dots, f_D^{-1}(\|\tau_n\|^{M(st),g}); v_t''' \rangle \in h_{pfun}(st)(\pi, n)$$

$$(A.92) \quad \langle v_1, \dots, v_n; v_t''' \rangle \in h_{pfun}(st)(\pi, n)$$

A.3.3 $\phi_1 \wedge \phi_2$

Translation rule

If $\phi_1, \phi_2 \in YNFORMS$ and λ is a TSQL2 value expression, then:

$$\begin{aligned} trans(\phi_1 \wedge \phi_2, \lambda) &\stackrel{def}{=} \\ &(\text{SELECT DISTINCT } \alpha_{1.1}, \alpha_{1.2}, \dots, \alpha_{1.n_1}, \alpha_{2.1}, \alpha_{2.2}, \dots, \alpha_{2.n_2} \\ &\quad \text{VALID VALID}(\alpha_1) \\ &\quad \text{FROM } trans(\phi_1, \lambda) \text{ AS } \alpha_1, trans(\phi_2, \lambda) \text{ AS } \alpha_2 \\ &\quad \text{WHERE } \dots \\ &\quad \text{AND } \dots \\ &\quad \vdots \\ &\quad \text{AND } \dots \\ &\quad \text{AND VALID}(\alpha_1) = \text{VALID}(\alpha_2)) \end{aligned}$$

n_1 and n_2 are the lengths of $\lceil \phi_1 \rceil$ and $\lceil \phi_2 \rceil$ respectively. Each time the translation rule is used, α_1 and α_2 are two new different correlation names, obtained by calling the correlation names generator after $trans(\phi_1, \lambda)$ and $trans(\phi_2, \lambda)$ have been computed. Assuming that $\lceil \phi_1 \rceil = \langle \tau_1^1, \dots, \tau_{n_1}^1 \rangle$ and $\lceil \phi_2 \rceil = \langle \tau_1^2, \dots, \tau_{n_2}^2 \rangle$, the “...”s in the WHERE clause are all the strings in S :

$$\begin{aligned} S = \{ & \text{“}\alpha_{1.i} = \alpha_{2.j}\text{”} \mid i \in \{1, 2, 3, \dots, n_1\}, j \in \{1, 2, 3, \dots, n_2\}, \\ & \tau_i^1 = \tau_j^2, \text{ and } \tau_i^1, \tau_j^2 \in VARS\} \end{aligned}$$

Proof that theorem 5.2 holds for $\phi = \phi_1 \wedge \phi_2$, if it holds for $\phi = \phi_1$ and $\phi = \phi_2$

I assume that $\phi_1, \phi_2 \in \text{YNFORMS}$. By the syntax of TOP, this implies that $\phi_1 \wedge \phi_2 \in \text{YNFORMS}$. I also assume that $st \in \text{PTS}$, λ is a TSQL2 value expression, $g^{db} \in G^{db}$, $eval(st, \lambda, g^{db}) \in D_P^*$, $\lceil \phi_1 \rceil = \langle \tau_1^1, \dots, \tau_{n_1}^1 \rangle$, $\lceil \phi_2 \rceil = \langle \tau_1^2, \dots, \tau_{n_2}^2 \rangle$, and $\Sigma = trans(\phi_1 \wedge \phi_2, \lambda)$. From the definition of $\lceil \dots \rceil$, it should be easy to see that $\lceil \phi_1 \wedge \phi_2 \rceil = \langle \tau_1^1, \dots, \tau_{n_1}^1, \tau_1^2, \dots, \tau_{n_2}^2 \rangle$. Finally, I assume that theorem 5.2 holds for $\phi = \phi_1$ and $\phi = \phi_2$. I need to show that:

1. $FCN(\Sigma) \subseteq FCN(\lambda)$
2. $eval(st, \Sigma, g^{db}) \in VREL_P(n_1 + n_2)$
3. $\langle v_1^1, \dots, v_{n_1}^1, v_1^2, \dots, v_{n_2}^2; v_t \rangle \in eval(st, \Sigma, g^{db})$ iff for some $g \in G$:

$$\begin{aligned} \|\tau_1^1\|^{M(st),g} &= f_D(v_1^1), \dots, \|\tau_{n_1}^1\|^{M(st),g} = f_D(v_{n_1}^1), \\ \|\tau_1^2\|^{M(st),g} &= f_D(v_1^2), \dots, \|\tau_{n_2}^2\|^{M(st),g} = f_D(v_{n_2}^2), \\ \|\phi_1 \wedge \phi_2\|^{M(st),st,f_D(v_t),f_D(eval(st,\lambda,g^{db})),g} &= T. \end{aligned}$$

Let Σ_1 and Σ_2 be the embedded SELECT statements in the FROM clause of Σ (i.e. $\Sigma_1 = trans(\phi_1, \lambda)$ and $\Sigma_2 = trans(\phi_2, \lambda)$). From the hypothesis, $\phi_1, \phi_2 \in \text{YNFORMS}$, $st \in \text{PTS}$, $\lceil \phi_1 \rceil = \langle \tau_1^1, \dots, \tau_{n_1}^1 \rangle$, $\lceil \phi_2 \rceil = \langle \tau_1^2, \dots, \tau_{n_2}^2 \rangle$, $g^{db} \in G^{db}$, and $eval(st, \lambda, g^{db}) \in D_P^*$. Then, from theorem 5.2 for $\phi = \phi_1$ (according to the hypothesis, theorem 5.2 holds for $\phi = \phi_1$ and $\phi = \phi_2$) we get:

- 1¹. $FCN(\Sigma_1) \subseteq FCN(\lambda)$
- 2¹. $eval(st, \Sigma_1, g^{db}) \in VREL_P(n_1)$
- 3¹. $\langle v_1^1, \dots, v_{n_1}^1; v_t \rangle \in eval(st, \Sigma_1, g^{db})$ iff for some $g_1 \in G$:

$$\begin{aligned} \|\tau_1^1\|^{M(st),g_1} &= f_D(v_1^1), \dots, \|\tau_{n_1}^1\|^{M(st),g_1} = f_D(v_{n_1}^1), \\ \|\phi_1\|^{M(st),st,f_D(v_t),f_D(eval(st,\lambda,g^{db})),g_1} &= T. \end{aligned}$$

and from theorem 5.2 for $\phi = \phi_2$:

- 1². $FCN(\Sigma_2) \subseteq FCN(\lambda)$
- 2². $eval(st, \Sigma_2, g^{db}) \in VREL_P(n_2)$
- 3². $\langle v_1^2, \dots, v_{n_2}^2; v_t \rangle \in eval(st, \Sigma_2, g^{db})$ iff for some $g_2 \in G$:

$$\begin{aligned} \|\tau_1^2\|^{M(st),g_2} &= f_D(v_1^2), \dots, \|\tau_{n_2}^2\|^{M(st),g_2} = f_D(v_{n_2}^2), \\ \|\phi_2\|^{M(st),st,f_D(v_t),f_D(eval(st,\lambda,g^{db})),g_2} &= T. \end{aligned}$$

Proof of clause 1

The two $\text{VALID}(\alpha_1)$ in the VALID and WHERE clauses of Σ , and the $\text{VALID}(\alpha_2)$ in the WHERE clause of Σ are not free column references in Σ , because Σ is a binding context for all of them. The $\alpha_1.1, \dots, \alpha_1.n_1, \alpha_2.1, \dots, \alpha_2.n_2$ in the SELECT clause of Σ , and any column

references of the form $\alpha_1.i$ or $\alpha_2.j$ in the **WHERE** clause of Σ ($i \in \{1, 2, 3, \dots, n_1\}$, $j \in \{1, 2, 3, \dots, n_2\}$; these column references derive from S) are not free column references in Σ for the same reason. Σ contains no other column references (and hence no other free column references), apart from those that possibly appear within Σ_1 or Σ_2 . By lemma A.1, this implies (A.93). (A.93), clause 1¹, and clause 1² imply clause 1.

$$(A.93) \quad FCN(\Sigma) \subseteq FCN(\Sigma_1) \cup FCN(\Sigma_2)$$

Proof of clause 2

When computing $eval(st, \Sigma, g^{db})$, α_1 and α_2 range over the tuples of $eval(st, \Sigma_1, g^{db})$ and $eval(st, \Sigma_2, g^{db})$ respectively. Clauses 2¹ and 2² imply that $eval(st, \Sigma_1, g^{db})$ and $eval(st, \Sigma_2, g^{db})$ are valid-time relations of n_1 and n_2 explicit attributes respectively. Hence, α_1 ranges over tuples $\langle v_1^1, \dots, v_{n_1}^1; v_t^1 \rangle \in eval(st, \Sigma_1, g^{db})$, and α_2 ranges over tuples $\langle v_1^2, \dots, v_{n_2}^2; v_t^2 \rangle \in eval(st, \Sigma_2, g^{db})$.

α_1 is generated after computing $\Sigma_2 = trans(\phi_2, \lambda)$ (see the translation rule). Hence, α_1 cannot appear in Σ_2 . Since α_1 does not appear in Σ_2 , for every tuple $\langle v_1^1, \dots, v_{n_1}^1; v_t^1 \rangle$:

$$(A.94) \quad eval(st, \Sigma_2, (g^{db})_{\langle v_1^1, \dots, v_{n_1}^1; v_t^1 \rangle}^{\alpha_1}) = eval(st, \Sigma_2, g^{db})$$

It should now be easy to see from the translation rule that (A.95) holds. $\langle v_1^1, \dots, v_{n_1}^1; v_t^1 \rangle$ is the tuple of $eval(st, \Sigma_1, g^{db})$ that corresponds to α_1 , while $\langle v_1^2, \dots, v_{n_2}^2; v_t^2 \rangle$ is the tuple of $eval(st, \Sigma_2, g^{db})$ that corresponds to α_2 . The last constraint in the **WHERE** clause of Σ requires the time-stamps of the two tuples to be identical. The last constraint in (A.95) corresponds to the constraints in the **WHERE** clause of Σ that derive from S (see also the comments about the equality predicate in section 5.3.6). I should have used $eval(st, \Sigma_2, (g^{db})_{\langle v_1^1, \dots, v_{n_1}^1; v_t^1 \rangle}^{\alpha_1})$ instead of $eval(st, \Sigma_2, g^{db})$, to capture the fact that if there is any free column reference of α_1 in Σ_2 , this has to be taken to refer to the $\langle v_1^1, \dots, v_{n_1}^1; v_t^1 \rangle$ tuple to which α_1 refers. By (A.94), however, $eval(st, \Sigma_2, (g^{db})_{\langle v_1^1, \dots, v_{n_1}^1; v_t^1 \rangle}^{\alpha_1})$ is the same as $eval(st, \Sigma_2, g^{db})$.

$$(A.95) \quad eval(st, \Sigma, g^{db}) = \{ \langle v_1^1, \dots, v_{n_1}^1, v_1^2, \dots, v_{n_2}^2; v_t \rangle \mid \\ \langle v_1^1, \dots, v_{n_1}^1; v_t \rangle \in eval(st, \Sigma_1, g^{db}), \\ \langle v_1^2, \dots, v_{n_2}^2; v_t \rangle \in eval(st, \Sigma_2, g^{db}), \text{ and} \\ \text{if } i \in \{1, 2, 3, \dots, n_1\}, j \in \{1, 2, 3, \dots, n_2\}, \tau_i^1, \tau_j^2 \in VARS, \text{ and } \tau_i^1 = \tau_j^2, \\ \text{then } v_i^1 = v_j^2 \}$$

According to (A.95), in every tuple of $eval(st, \Sigma, g^{db})$, the time-stamp v_t is also the time-stamp of a tuple in $eval(st, \Sigma_1, g^{db})$. By clause 1¹, $eval(st, \Sigma_1, g^{db}) \in VREL_P(n_1)$, which implies that $v_t \in D_P$. Hence, all the time-stamps of $eval(st, \Sigma, g^{db})$ are elements of D_P . (A.95) also implies that $eval(st, \Sigma, g^{db})$ is a valid-time relation of $n_1 + n_2$ explicit attributes. Hence, $eval(st, \Sigma, g^{db}) \in VREL_P(n_1 + n_2)$. Clause 2 has been proven.

Proof of clause 3

Using the definition of $\|\phi_1 \wedge \phi_2\|^{M(st),st,et,lt,g}$ (section 3.6), clause 3 becomes:

$$\langle v_1^1, \dots, v_{n_1}^1, v_1^2, \dots, v_{n_2}^2; v_t \rangle \in eval(st, \Sigma, g^{db}) \text{ iff for some } g :$$

$$(A.96) \quad g \in G$$

$$(A.97) \quad \|\tau_1^1\|^{M(st),g} = f_D(v_1^1), \dots, \|\tau_{n_1}^1\|^{M(st),g} = f_D(v_{n_1}^1)$$

$$(A.98) \quad \|\tau_1^2\|^{M(st),g} = f_D(v_1^2), \dots, \|\tau_{n_2}^2\|^{M(st),g} = f_D(v_{n_2}^2)$$

$$(A.99) \quad \|\phi_1\|^{M(st),st,f_D(v_t),f_D(eval(st,\lambda,g^{db})),g} = T$$

$$(A.100) \quad \|\phi_2\|^{M(st),st,f_D(v_t),f_D(eval(st,\lambda,g^{db})),g} = T$$

I first prove the forward direction of clause 3. I assume that (A.101) holds. I need to prove that for some g , (A.96) – (A.100) also hold.

$$(A.101) \quad \langle v_1^1, \dots, v_{n_1}^1, v_1^2, \dots, v_{n_2}^2; v_t \rangle \in eval(st, \Sigma, g^{db})$$

(A.101) and (A.95) imply that:

$$(A.102) \quad \langle v_1^1, \dots, v_{n_1}^1; v_t \rangle \in eval(st, \Sigma_1, g^{db})$$

$$(A.103) \quad \langle v_1^2, \dots, v_{n_2}^2; v_t \rangle \in eval(st, \Sigma_2, g^{db})$$

$$(A.104) \quad \text{if } i \in \{1, 2, 3, \dots, n_1\}, j \in \{1, 2, 3, \dots, n_2\}, \tau_i^1, \tau_j^2 \in VARS, \text{ and } \tau_i^1 = \tau_j^2, \\ \text{then } v_i^1 = v_j^2$$

(A.102) and clause 3¹ imply that for some g_1 :

$$(A.105) \quad g_1 \in G$$

$$(A.106) \quad \|\tau_1^1\|^{M(st),g_1} = f_D(v_1^1), \dots, \|\tau_{n_1}^1\|^{M(st),g_1} = f_D(v_{n_1}^1)$$

$$(A.107) \quad \|\phi_1\|^{M(st),st,f_D(v_t),f_D(eval(st,\lambda,g^{db})),g_1} = T$$

Similarly, (A.103) and clause 3² imply that for some g_2 :

$$(A.108) \quad g_2 \in G$$

$$(A.109) \quad \|\tau_1^2\|^{M(st),g_2} = f_D(v_1^2), \dots, \|\tau_{n_2}^2\|^{M(st),g_2} = f_D(v_{n_2}^2)$$

$$(A.110) \quad \|\phi_2\|^{M(st),st,f_D(v_t),f_D(eval(st,\lambda,g^{db})),g_2} = T$$

I define the mapping $g : VARS \mapsto OBJS$ as follows:

$$g(\beta) \stackrel{def}{=} \begin{cases} g_1(\beta), & \text{if for some } i \in \{1, 2, 3, \dots, n_1\}, \beta = \tau_i^1 \\ g_2(\beta), & \text{if for some } j \in \{1, 2, 3, \dots, n_2\}, \beta = \tau_j^2 \\ o, & \text{otherwise} \end{cases}$$

where o is a particular element of $OBJS$, chosen arbitrarily. (A.96) follows from lemma A.6, the definition of g , (A.104), (A.106), and (A.109).

The definition of g implies that g and g_1 assign the same values to all the variables among $\tau_1^1, \dots, \tau_{n_1}^1$. The assumption that $\ulcorner \phi_1 \urcorner = \langle \tau_1^1, \dots, \tau_{n_1}^1 \rangle$ and the definition of $\ulcorner \phi_1 \urcorner$

imply that all the variables of ϕ_1 are among $\tau_1^1, \dots, \tau_{n_1}^1$. Hence, g and g_1 assign the same values to all the variables in ϕ_1 . (A.97) follows from lemma A.3, the assumption that $\langle \tau_1^1, \dots, \tau_{n_1}^1 \rangle = \lceil \phi_1 \rceil$, (A.106), and the fact that g and g_1 assign the same values to all the variables of ϕ_1 . The proof of (A.98) is very similar.

I now prove (A.99). The fact that g and g_1 assign the same values to all the variables of ϕ_1 implies (A.111). (A.111) and (A.107) imply (A.99). The proof of (A.100) is very similar. This concludes the proof of the forward direction of clause 3.

$$(A.111) \quad \|\phi_1\|^{M(st), st, f_D(v_t), f_D(eval(st, \lambda, g^{db})), g} = \|\phi_1\|^{M(st), st, f_D(v_t), f_D(eval(st, \lambda, g^{db})), g_1}$$

I now prove the backwards direction of clause 3. I assume that for some g , (A.96) – (A.100) hold. I need to prove that $\langle v_1^1, \dots, v_{n_1}^1, v_1^2, \dots, v_{n_2}^2; v_t \rangle \in eval(st, \Sigma, g^{db})$. According to (A.95), it is enough to prove (A.102) – (A.104). Clause 3¹, (A.96), (A.97), and (A.99) imply (A.102). Clause 3², (A.96), (A.98), and (A.100) imply (A.103).

It remains to prove (A.104). Let us assume that $i \in \{1, 2, 3, \dots, n_1\}$, $j \in \{1, 2, 3, \dots, n_2\}$, $\tau_i^1, \tau_j^2 \in VARS$, and $\tau_i^1 = \tau_j^2$. (A.97) and (A.98) imply that $f_D(v_i^1) = f_D(v_j^2)$. This in turn implies that $f_D^{-1}(f_D(v_i^1)) = f_D^{-1}(f_D(v_j^2))$, i.e. that $v_i^1 = v_j^2$. (A.104) and the backwards direction of clause 3 have been proven.

A.3.4 $Pres[\phi']$

Translation rule

If $\phi' \in YNFORMS$ and λ is a TSQL2 value expression, then:

$$trans(Pres[\phi'], \lambda) \stackrel{def}{=} \\ \text{(SELECT DISTINCT } \alpha.1, \alpha.2, \dots, \alpha.n \\ \text{VALID VALID}(\alpha) \\ \text{FROM } trans(\phi', \lambda) \text{ AS } \alpha \\ \text{WHERE VALID}(\alpha) \text{ CONTAINS TIMESTAMP 'now'})$$

n is the length of $\lceil \phi' \rceil$. Each time the translation rule is used, α is a new correlation name, obtained by calling the correlation names generator.

Proof that theorem 5.2 holds for $\phi = Pres[\phi']$, if it holds for $\phi = \phi'$

I assume that $\phi' \in YNFORMS$. By the syntax of TOP, this implies that $Pres[\phi'] \in YNFORMS$. I also assume that $st \in PTS$, λ is a TSQL2 value expression, $g^{db} \in G^{db}$, $eval(st, \lambda, g^{db}) \in D_P^*$, $\lceil \phi' \rceil = \langle \tau_1, \tau_2, \tau_3, \dots, \tau_n \rangle$, and $\Sigma = trans(Pres[\phi'], \lambda)$. From the definition of $\lceil \dots \rceil$, it should be easy to see that $\lceil Pres[\phi'] \rceil = \lceil \phi' \rceil = \langle \tau_1, \dots, \tau_n \rangle$. Finally, I assume that theorem 5.2 holds for $\phi = \phi'$. I need to show that:

1. $FCN(\Sigma) \subseteq FCN(\lambda)$
2. $eval(st, \Sigma, g^{db}) \in VREL_P(n)$

3. $\langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$ iff for some $g \in G$:
 $\|\tau_1\|^{M(st),g} = f_D(v_1), \dots, \|\tau_n\|^{M(st),g} = f_D(v_n)$, and
 $\|Pres[\phi']\|^{M(st),st,f_D(v_t),f_D(eval(st,\lambda,g^{db})),g} = T$

Let Σ' be the embedded SELECT statement in the FROM clause of Σ , i.e. $\Sigma' = trans(\phi', \lambda)$. From the hypothesis, $\phi' \in YNFORMS$, $st \in PTS$, $\lceil \phi' \rceil = \langle \tau_1, \dots, \tau_n \rangle$, $g^{db} \in G^{db}$, and $eval(st, \lambda, g^{db}) \in D_P^*$. Then, from theorem 5.2 for $\phi = \phi'$ (according to the hypothesis, theorem 5.2 holds for $\phi = \phi'$) we get:

$$1'. FCN(\Sigma') \subseteq FCN(\lambda)$$

$$2'. eval(st, \Sigma', g^{db}) \in VREL_P(n)$$

- 3'. $\langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma', g^{db})$ iff for some $g \in G$:
 $\|\tau_1\|^{M(st),g} = f_D(v_1), \dots, \|\tau_n\|^{M(st),g} = f_D(v_n)$, and
 $\|\phi'\|^{M(st),st,f_D(v_t),f_D(eval(st,\lambda,g^{db})),g} = T$

Proof of clause 1

The two $VALID(\alpha)$ in the VALID and WHERE clauses of Σ are not free column references in Σ , because Σ is a binding context for both of them. The $\alpha.1, \dots, \alpha.n$ in the SELECT clause of Σ are not free column references in Σ for the same reason. Σ contains no other column references (and hence no other free column references), apart from those that possibly appear within Σ' . By lemma A.1, this implies (A.112). (A.112) and clause 1' imply clause 1.

$$(A.112) \quad FCN(\Sigma) \subseteq FCN(\Sigma')$$

Proof of clause 2

Given that $eval(st, \Sigma', g^{db}) \in VREL_P(n)$ (from clause 2'), it should be easy to see from the translation rule that:

$$(A.113) \quad eval(st, \Sigma, g^{db}) = \{\langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma', g^{db}) \mid st \in f_D(v_t)\}$$

By (A.113), any time-stamp v_t in $eval(st, \Sigma, g^{db})$ is also a time-stamp in $eval(st, \Sigma', g^{db})$. This implies that $v_t \in D_P$, because $eval(st, \Sigma', g^{db}) \in VREL_P(n)$. (A.113) also implies that $eval(st, \Sigma, g^{db})$ is a valid-time relation of n explicit attributes. Therefore, $eval(st, \Sigma, g^{db}) \in VREL_P(n)$. Clause 2 has been proven.

Proof of clause 3

Using the definition of $\|Pres[\phi']\|^{M(st),st,et,lt,g}$ (section 3.7), clause 3 becomes:

$$(A.114) \quad \begin{aligned} &\langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db}) \text{ iff for some } g \in G : \\ &\|\tau_1\|^{M(st),g} = f_D(v_1), \dots, \|\tau_n\|^{M(st),g} = f_D(v_n), \\ &st \in f_D(v_t), \text{ and } \|\phi'\|^{M(st),st,f_D(v_t),f_D(eval(st,\lambda,g^{db})),g} = T \end{aligned}$$

I first prove the forward direction of (A.114). If $\langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$, then according to (A.113):

$$(A.115) \quad \langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma', g^{db})$$

$$(A.116) \quad st \in f_D(v_t)$$

(A.115), clause 3', and (A.116) imply that for some $g \in G$:

$$(A.117) \quad \begin{aligned} \|\tau_1\|^{M(st),g} = f_D(v_1), \dots, \|\tau_n\|^{M(st),g} = f_D(v_n) \\ st \in f_D(v_t), \text{ and } \|\phi'\|^{M(st),st,f_D(v_t),f_D(eval(st,\lambda,g^{db})),g} = T \end{aligned}$$

The forward direction of (A.114) has been proven. I now prove the backwards direction of (A.114). If for some $g \in G$, (A.117) holds, then according to clause 3', (A.118) is true. Also (A.117) implies (A.119). (A.118), (A.119), and (A.113) imply that $\langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$. The backwards direction of (A.114) has been proven.

$$(A.118) \quad \langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma', g^{db})$$

$$(A.119) \quad st \in f_D(v_t)$$

A.3.5 $Past[\beta, \phi']$

Translation rule

If $\beta \in VARS$, $\phi' \in YNFORMS$, and λ is a TSQL2 value expression, then:

$$\begin{aligned} trans(Past[\beta, \phi'], \lambda) &\stackrel{def}{=} \\ (SELECT DISTINCT VALID(\alpha), \alpha.1, \alpha.2, \dots, \alpha.n \\ &\quad VALID VALID(\alpha) \\ &\quad FROM trans(\phi', \lambda') AS \alpha) \end{aligned}$$

λ' is the expression $INTERSECT(\lambda, PERIOD(TIMESTAMP 'beginning', TIMESTAMP 'now' - INTERVAL '1' \chi))$, χ is the TSQL2 name of the granularity of chronons (e.g. DAY if chronons correspond to days), and n is the length of $\lceil \phi' \rceil$. Each time the translation rule is used, α is a new correlation name, obtained by calling the correlation names generator.

Proof that theorem 5.2 holds for $\phi = Past[\beta, \phi']$, if it holds for $\phi = \phi'$

I assume that $\beta \in VARS$ and $\phi' \in YNFORMS$. By the syntax of TOP, this implies that $Past[\beta, \phi'] \in YNFORMS$. I also assume that $st \in PTS$, λ is a TSQL2 value expression, λ' is as in the translation rule, $g^{db} \in G^{db}$, $eval(st, \lambda, g^{db}) \in D_P^*$, $\lceil \phi' \rceil = \langle \tau_1, \tau_2, \tau_3, \dots, \tau_n \rangle$, and $\Sigma = trans(Past[\beta, \phi'], \lambda)$. From the definition of $\lceil \dots \rceil$, it should be easy to see that $\lceil Past[\beta, \phi'] \rceil = \langle \beta, \tau_1, \dots, \tau_n \rangle$. Finally, I assume that theorem 5.2 holds for $\phi = \phi'$. I need to show that:

1. $FCN(\Sigma) \subseteq FCN(\lambda)$

2. $eval(st, \Sigma, g^{db}) \in VREL_P(n+1)$
3. $\langle v, v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$ iff for some $g \in G$:
 $\|\beta\|^{M(st),g} = f_D(v)$, $\|\tau_1\|^{M(st),g} = f_D(v_1)$, \dots , $\|\tau_n\|^{M(st),g} = f_D(v_n)$, and
 $\|Past[\beta, \phi']\|^{M(st, st, f_D(v_t), f_D(eval(st, \lambda, g^{db})), g)} = T$

The definition of λ' implies that any free column reference in λ' is situated within the λ of λ' . By lemma A.1, this implies (A.120). Also, the syntax of TSQL2 and the fact that λ is a value expression imply that λ' is a value expression as well.

$$(A.120) \quad FCN(\lambda') \subseteq FCN(\lambda)$$

The assumption that $eval(st, \lambda, g^{db}) \in D_P^*$ and the definition of λ' imply (A.121) and that $eval(st, \lambda', g^{db}) \in D_P^*$.

$$(A.121) \quad f_D(eval(st, \lambda', g^{db})) = f_D(eval(st, \lambda, g^{db})) \cap [t_{first}, st)$$

Let Σ' be the embedded SELECT statement in the FROM clause of Σ , i.e. $\Sigma' = trans(\phi', \lambda')$. From the hypothesis, $\phi' \in YNFORMS$, $st \in PTS$, $\lceil \phi' \rceil = \langle \tau_1, \dots, \tau_n \rangle$, and $g^{db} \in G^{db}$. From the discussion above, λ' is a value expression, and $eval(st, \lambda', g^{db}) \in D_P^*$. Then, from theorem 5.2 for $\phi = \phi'$ (according to the hypothesis, theorem 5.2 holds for $\phi = \phi'$):

- 1'. $FCN(\Sigma') \subseteq FCN(\lambda')$
- 2'. $eval(st, \Sigma', g^{db}) \in VREL_P(n)$
- 3'. $\langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma', g^{db})$ iff for some $g' \in G$:
 $\|\tau_1\|^{M(st),g'} = f_D(v_1)$, \dots , $\|\tau_n\|^{M(st),g'} = f_D(v_n)$, and
 $\|\phi'\|^{M(st, st, f_D(v_t), f_D(eval(st, \lambda', g^{db})), g')} = T$

Proof of clause 1

The two $VALID(\alpha)$ in the SELECT and VALID clauses of Σ are not free column references in Σ , because Σ is a binding context for both of them. The $\alpha.1, \dots, \alpha.n$ in the SELECT clause of Σ are not free column references in Σ for the same reason. Σ contains no other column references (and hence no other free column references), apart from those that possibly appear within Σ' . By lemma A.1, this implies (A.122). (A.122), clause 1', and (A.120) imply clause 1.

$$(A.122) \quad FCN(\Sigma) \subseteq FCN(\Sigma')$$

Proof of clause 2

According to clause 2', $eval(st, \Sigma', g^{db}) \in VREL_P(n)$. Then, from the translation rule, it should be easy to see that (A.123) holds.

$$(A.123) \quad eval(st, \Sigma, g^{db}) = \{ \langle v_t, v_1, \dots, v_n; v_t \rangle \mid \langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma', g^{db}) \}$$

(A.123) implies that all the time-stamps v_t of $eval(st, \Sigma, g^{db})$ are also time-stamps of $eval(st, \Sigma', g^{db})$. This implies that $v_t \in D_P$, because $eval(st, \Sigma', g^{db}) \in VREL_P(n)$. (A.123) also implies that $eval(st, \Sigma, g^{db})$ is a valid-time relation of $n + 1$ explicit attributes. Therefore, $eval(st, \Sigma, g^{db}) \in VREL_P(n + 1)$. Clause 2 has been proven.

Proof of clause 3

Using the definition of $\|Past[\beta, \phi']\|^{st, et, lt, g}$ (section 3.8) and the fact that $\|\beta\|^{M(st), g} = g(\beta)$, clause 3 becomes:

$$\begin{aligned}
 & \langle v, v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db}) \text{ iff for some } g : \\
 (A.124) \quad & g \in G \\
 (A.125) \quad & g(\beta) = f_D(v) \\
 (A.126) \quad & \|\tau_1\|^{M(st), g} = f_D(v_1), \dots, \|\tau_n\|^{M(st), g} = f_D(v_n) \\
 (A.127) \quad & g(\beta) = f_D(v_t) \\
 (A.128) \quad & \|\phi'\|^{st, f_D(v_t), f_D(eval(st, \lambda, g^{db})) \cap [t_{first}, st], g} = T
 \end{aligned}$$

I first prove the forward direction of clause 3. I assume that $\langle v, v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$. I need to prove that for some g , (A.124) – (A.128) hold. The assumption that $\langle v, v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$ and (A.123) imply that:

$$\begin{aligned}
 (A.129) \quad & v = v_t \\
 (A.130) \quad & \langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma', g^{db})
 \end{aligned}$$

(A.130) and clause 3' imply that for some g' :

$$\begin{aligned}
 (A.131) \quad & g' \in G \\
 (A.132) \quad & \|\tau_1\|^{M(st), g'} = f_D(v_1), \dots, \|\tau_n\|^{M(st), g'} = f_D(v_n) \\
 (A.133) \quad & \|\phi'\|^{M(st), st, f_D(v_t), f_D(eval(st, \lambda', g^{db})), g'} = T
 \end{aligned}$$

Let $g = (g')_{f_D(v_t)}^\beta$. Clause 2 (proven above) and the assumption that $\langle v, v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$ imply that $v_t \in D_P$, a fact that along with lemma A.7, the assumption that $\beta \in VARS$, (A.131), and the definition of g imply (A.124). (A.127) follows from the definition of g . (A.125) follows from (A.127) and (A.129).

(A.133) and (A.121) imply (A.134)

$$(A.134) \quad \|\phi'\|^{M(st), st, f_D(v_t), f_D(eval(st, \lambda, g^{db})) \cap [t_{first}, st], g'} = T$$

The syntax of TOP (section 3.2) and the fact that $Past[\beta, \phi'] \in YNFORMS$, imply that β does not occur in ϕ' . This and the definition of g imply (A.135). (A.134) and (A.135) imply (A.128).

$$\begin{aligned}
 (A.135) \quad & \|\phi'\|^{M(st), st, f_D(v_t), f_D(eval(st, \lambda, g^{db})) \cap [t_{first}, st], g'} = \\
 & \|\phi'\|^{M(st), st, f_D(v_t), f_D(eval(st, \lambda, g^{db})) \cap [t_{first}, st], (g')_{f_D(v_t)}^\beta} = \\
 & \|\phi'\|^{M(st), st, f_D(v_t), f_D(eval(st, \lambda, g^{db})) \cap [t_{first}, st], g}
 \end{aligned}$$

(A.126) follows from lemma A.3, the assumption that $\lceil \phi' \rceil = \langle \tau_1, \dots, \tau_n \rangle$, (A.132), and the fact that g and g' assign the same values to all variables, possibly apart from β , which does not occur in ϕ' . The forward direction of clause 3 has been proven.

I now prove the backwards direction of clause 3. I assume that (A.124) – (A.128) hold. I need to prove that $\langle v, v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$. According to (A.123), it is enough to prove (A.129) and (A.130). According to clause 3', in order to prove (A.130), it is enough to prove (A.136) – (A.138). (A.136) and (A.137) are the same as (A.124) and (A.126), which were assumed to hold. (A.138) follows from (A.128) and (A.121).

$$(A.136) \quad g \in G$$

$$(A.137) \quad \|\tau_1\|^{M(st),g} = f_D(v_1), \dots, \|\tau_n\|^{M(st),g} = f_D(v_n)$$

$$(A.138) \quad \|\phi'\|^{M(st),st,f_D(v_t),f_D(eval(st,\lambda',g^{db})),g} = T$$

It remains to prove (A.129). From (A.125) and (A.127) we get $f_D(v_t) = f_D(v)$, which implies that $f_D^{-1}(f_D(v_t)) = f_D^{-1}(f_D(v))$, i.e. $v = v_t$. Hence, (A.129) holds. The backwards direction of clause 3 has been proven.

A.3.6 $Perf[\beta, \phi']$

Translation rule

If $\beta \in VARS$, $\phi' \in YNFORMS$, and λ is a TSQL2 value expression, then:

$$\begin{aligned} trans(Perf[\beta, \phi'], \lambda) &\stackrel{def}{=} \\ &(\text{SELECT DISTINCT VALID}(\alpha), \alpha.1, \alpha.2, \dots, \alpha.n \\ &\quad \text{VALID INTERSECT}(\lambda, \text{PERIOD}(\text{END}(\text{VALID}(\alpha)) + \text{INTERVAL '1' } \chi, \\ &\quad \quad \quad \text{TIMESTAMP 'forever'})) \\ &\quad \text{FROM } trans(\phi', \lambda_{init}) \text{ AS } \alpha \\ &)(\text{SUBPERIOD}) \end{aligned}$$

λ_{init} is as in section 5.10, χ is the TSQL2 name of the granularity of chronons, and n is the length of $\lceil \phi' \rceil$. Each time the translation rule is used, α is a new correlation name, obtained by calling the correlation names generator after λ has been supplied.

Proof that theorem 5.2 holds for $\phi = Perf[\beta, \phi']$, if it holds for $\phi = \phi'$

I assume that $\beta \in VARS$ and $\phi' \in YNFORMS$. By the syntax of TOP, this implies that $Perf[\beta, \phi'] \in YNFORMS$. I also assume that $st \in PTS$, λ is a TSQL2 value expression, λ_{init} is as in section 5.10, $g^{db} \in G^{db}$, $eval(st, \lambda, g^{db}) \in D_P^*$, $\lceil \phi' \rceil = \langle \tau_1, \tau_2, \tau_3, \dots, \tau_n \rangle$, and $\Sigma = trans(Perf[\beta, \phi'], \lambda)$. From the definition of $\lceil \dots \rceil$, it should be easy to see that $\lceil Perf[\beta, \phi'] \rceil = \langle \beta, \tau_1, \dots, \tau_n \rangle$. Finally, I assume that theorem 5.2 holds for $\phi = \phi'$. I need to show that:

1. $FCN(\Sigma) \subseteq FCN(\lambda)$

2. $eval(st, \Sigma, g^{db}) \in VREL_P(n+1)$
3. $\langle v, v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$ iff for some $g \in G$:
 $\|\beta\|^{M(st),g} = f_D(v)$, $\|\tau_1\|^{M(st),g} = v_1, \dots, \|\tau_n\|^{M(st),g} = v_n$, and
 $\|Perf[\beta, \phi']\|^{M(st),st,f_D(v_t),f_D(eval(st,\lambda,g^{db})),g} = T$

According to the syntax of TSQL2, λ_{init} is a value expression. By lemma 5.1, (A.139) – (A.141) hold.

$$(A.139) \quad f_D(eval(st, \lambda_{init}, g^{db})) = PTS$$

$$(A.140) \quad eval(st, \lambda_{init}, g^{db}) \in D_P^*$$

$$(A.141) \quad FCN(\lambda_{init}) = \emptyset$$

Let Σ' be the **SELECT** statement in the **FROM** clause of Σ , i.e. $\Sigma' = trans(\phi', \lambda_{init})$. From the hypothesis, $\phi' \in YNFORMS$, $st \in PTS$, $\lceil \phi' \rceil = \langle \tau_1, \dots, \tau_n \rangle$, and $g^{db} \in G^{db}$. From the discussion above, λ_{init} is a TSQL2 value expression, and $eval(st, \lambda_{init}, g^{db}) \in D_P^*$. Then, from theorem 5.2 for $\phi = \phi'$ (according to the hypothesis, theorem 5.2 holds for $\phi = \phi'$), and using (A.139) and (A.141), we get:

$$1'. FCN(\Sigma') \subseteq \emptyset$$

$$2'. eval(st, \Sigma', g^{db}) \in VREL_P(n)$$

$$3'. \langle v_1, \dots, v_n; v'_t \rangle \in eval(st, \Sigma', g^{db}) \text{ iff for some } g' \in G:$$

$$\|\tau_1\|^{M(st),g'} = f_D(v_1), \dots, \|\tau_n\|^{M(st),g'} = f_D(v_n), \text{ and}$$

$$\|\phi'\|^{M(st),st,f_D(v'_t),PTS,g'} = T$$

Proof of clause 1

The two **VALID**(α) in the **SELECT** and **VALID** clauses of Σ are not free column references in Σ , because Σ is a binding context for both of them. The $\alpha.1, \dots, \alpha.n$ in the **SELECT** clause of Σ are not free column references in Σ for the same reason. Σ contains no other column references (and hence no other free column references), apart from those that possibly appear within Σ' or the λ in the **VALID** clause of Σ . By lemma A.1, this implies (A.142). Clause 1' and (A.142) imply clause 1.

$$(A.142) \quad FCN(\Sigma) \subseteq FCN(\Sigma') \cup FCN(\lambda)$$

Proof of clause 2

When computing $eval(st, \Sigma, g^{db})$, the α of Σ ranges over the tuples of $eval(st, \Sigma', g^{db})$. By clause 2', this implies that α ranges over tuples of the form $\langle v_1, \dots, v_n; v'_t \rangle$, where $v'_t \in D_P$. α is generated by calling the correlation names generator after λ has been supplied. Hence, α cannot appear in λ . The fact that α does not appear in λ means that for every tuple $\langle v_1, \dots, v_n; v'_t \rangle$:

$$(A.143) \quad eval(st, \lambda, (g^{db})_{\langle v_1, \dots, v_n; v'_t \rangle}^\alpha) = eval(st, \lambda, g^{db})$$

The reader should now be able to see that (A.144) holds. Intuitively, $\langle v_1, \dots, v_n; v'_t \rangle$ is the tuple to which α refers. For each α -tuple $\langle v_1, \dots, v_n; v'_t \rangle$, the **SELECT** and **VALID** clauses of Σ generate a new tuple $\langle v, v_1, \dots, v_n; v''_t \rangle$, where $v = v'_t$ (the old time-stamp), and v''_t (the new time-stamp) represents the intersection of $eval(st, \lambda, g^{db})$ with the period (or empty set) that begins immediately after the end of $f_D(v'_t)$ and ends at the end of the time-axis. The restriction $f_D(v''_t) \neq \emptyset$ is needed to capture the fact that when evaluating Σ , new tuples of the form $\langle v, v_1, \dots, v_n; v''_t \rangle$ are automatically removed from the resulting relation if $f_D(v''_t) = \emptyset$. (The time-stamps of valid-time relations must represent temporal elements, which are non-empty sets of chronons; see section 5.2.3.)

$$(A.144) \quad \begin{aligned} eval(st, \Sigma, g^{db}) &= subperiod(\{ \langle v, v_1, \dots, v_n; v''_t \rangle \mid \text{for some } v'_t, \\ &\langle v_1, \dots, v_n; v'_t \rangle \in eval(st, \Sigma', g^{db}), \\ &f_D(v''_t) = f_D(eval(st, \lambda, g^{db})) \cap (maxpt(f_D(v'_t)), t_{last}], \\ &f_D(v''_t) \neq \emptyset, \text{ and } v = v'_t \} \end{aligned}$$

In (A.144), I should have used $eval(st, \lambda, (g^{db})^\alpha_{\langle v_1, \dots, v_n; v'_t \rangle})$ instead of $eval(st, \lambda, g^{db})$, to capture the fact that if there is any free column reference of α in λ , this has to be taken to refer to the $\langle v_1, \dots, v_n; v'_t \rangle$ tuple to which α refers. By (A.143), however, $eval(st, \lambda, (g^{db})^\alpha_{\langle v_1, \dots, v_n; v'_t \rangle})$ is the same as $eval(st, \lambda, g^{db})$.

Using the definition of *subperiod* (section 5.3.2), (A.144) becomes (A.145). (The $f_D(v_t) \subseteq f_D(v''_t)$ of (A.145) implies that $f_D(v''_t)$ is a period, i.e. a non-empty set. Hence, the constraint $f_D(v''_t) \neq \emptyset$ of (A.144) is not needed in (A.145).)

$$(A.145) \quad \begin{aligned} eval(st, \Sigma, g^{db}) &= \{ \langle v, v_1, \dots, v_n; v_t \rangle \mid \text{for some } v'_t, v''_t, \\ &\langle v_1, \dots, v_n; v'_t \rangle \in eval(st, \Sigma', g^{db}), \\ &f_D(v''_t) = f_D(eval(st, \lambda, g^{db})) \cap (maxpt(f_D(v'_t)), t_{last}], \\ &v = v'_t, \text{ and } f_D(v_t) \subseteq f_D(v''_t) \} \end{aligned}$$

(A.145) is equivalent to (A.146).

$$(A.146) \quad \begin{aligned} eval(st, \Sigma, g^{db}) &= \{ \langle v, v_1, \dots, v_n; v_t \rangle \mid \text{for some } v'_t, \\ &\langle v_1, \dots, v_n; v'_t \rangle \in eval(st, \Sigma', g^{db}), v = v'_t, \text{ and} \\ &f_D(v_t) \subseteq f_D(eval(st, \lambda, g^{db})) \cap (maxpt(f_D(v'_t)), t_{last}] \} \end{aligned}$$

For every tuple $\langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$, the $f_D(v_t) \subseteq f_D(eval(st, \lambda, g^{db})) \cap (maxpt(f_D(v'_t)), t_{last}]$ in (A.146) implies that $f_D(v_t)$ is a period, which in turn implies that $v_t \in D_P$. (A.146) also implies that $eval(st, \Sigma, g^{db})$ is a valid-time relation of $n+1$ explicit attributes. Hence, $eval(st, \Sigma, g^{db}) \in VREL_P(n+1)$. Clause 2 has been proven.

Proof of clause 3

Using the definition of $\|Perf[\beta, \phi']\|^{M(st), st, et, lt, g}$ (see section 3.15), and the fact that $\|\beta\|^{M(st), g} = g(\beta)$, clause 3 becomes:

$$\begin{aligned}
 (A.147) \quad & \langle v, v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db}) \text{ iff for some } g \text{ and } et' : \\
 (A.148) \quad & g \in G \\
 (A.149) \quad & et' \in PERIODS \\
 (A.150) \quad & g(\beta) = f_D(v) \\
 (A.151) \quad & \|\tau_1\|^{M(st), g} = f_D(v_1), \dots, \|\tau_n\|^{M(st), g} = f_D(v_n) \\
 (A.152) \quad & g(\beta) = et' \\
 (A.153) \quad & f_D(v_t) \sqsubseteq f_D(eval(st, \lambda, g^{db})) \\
 (A.154) \quad & maxpt(et') \prec minpt(f_D(v_t)) \\
 (A.155) \quad & \|\phi'\|^{M(st), st, et', PTS, g} = T
 \end{aligned}$$

I first prove the forward direction of clause 3. I assume that $\langle v, v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$. I need to prove that for some g and et' , (A.147) – (A.154) hold. The assumption that $\langle v, v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$, and (A.146) imply that for some v'_t :

$$\begin{aligned}
 (A.155) \quad & \langle v_1, \dots, v_n; v'_t \rangle \in eval(st, \Sigma', g^{db}) \\
 (A.156) \quad & f_D(v_t) \sqsubseteq f_D(eval(st, \lambda, g^{db})) \cap (maxpt(f_D(v'_t)), t_{last}] \\
 (A.157) \quad & v = v'_t
 \end{aligned}$$

I set et' as in (A.158) and show that (A.147) – (A.154) hold.

$$(A.158) \quad et' = f_D(v'_t)$$

(A.155) and clause 3' imply that for some g' :

$$\begin{aligned}
 (A.159) \quad & g' \in G \\
 (A.160) \quad & \|\tau_1\|^{M(st), g'} = f_D(v_1), \dots, \|\tau_n\|^{M(st), g'} = f_D(v_n) \\
 (A.161) \quad & \|\phi'\|^{M(st), st, f_D(v'_t), PTS, g'} = T
 \end{aligned}$$

Let $g = (g')_{f_D(v'_t)}^\beta$. (A.155) and clause 2' imply that $v'_t \in D_P$. By lemma A.7, (A.147) holds. (A.151) follows from the definition of g and (A.158). The conclusion that $v'_t \in D_P$ implies that $f_D(v'_t) \in PERIODS$. This and (A.158) imply (A.148). The definition of g and (A.157) imply (A.149).

I now prove (A.154). The syntax of TOP (section 3.2) and the fact that $Perf[\beta, \phi'] \in YNFORMS$, imply that β does not occur in ϕ' . Along with the definition of g , this implies (A.162). (A.161), (A.158), and (A.162) imply (A.154).

$$\begin{aligned}
 (A.162) \quad & \|\phi'\|^{M(st), st, et', PTS, g'} = \\
 & \|\phi'\|^{M(st), st, et', PTS, (g')_{f_D(v'_t)}^\beta} = \\
 & \|\phi'\|^{M(st), st, et', PTS, g}
 \end{aligned}$$

(A.150) follows from lemma A.3, the assumption that $\lceil \phi' \rceil = \langle \tau_1, \dots, \tau_n \rangle$, (A.160), and the fact that g and g' assign the same values to all variables, possibly apart from β , which does not occur in ϕ' .

I now prove (A.152). (A.156) and the definition of \sqsubseteq imply (A.163) and (A.164). (A.164) in turn implies (A.165).

$$(A.163) \quad f_D(v_t) \in PERIODS$$

$$(A.164) \quad f_D(v_t) \subseteq f_D(eval(st, \lambda, g^{db})) \cap (maxpt(f_D(v'_t)), t_{last}]$$

$$(A.165) \quad f_D(v_t) \subseteq f_D(eval(st, \lambda, g^{db}))$$

From the hypothesis, $eval(st, \lambda, g^{db}) \in D_P^*$, which implies that $f_D(eval(st, \lambda, g^{db}))$ is the empty set or a period. $f_D(eval(st, \lambda, g^{db}))$ cannot be the empty set, because according to (A.165), it has $f_D(v_t)$ as its subset, and by (A.163) $f_D(v_t)$ is a period, i.e. a non-empty set. Hence, (A.166) holds. (A.165), (A.163), and (A.166) imply (A.152).

$$(A.166) \quad f_D(eval(st, \lambda, g^{db})) \in PERIODS$$

It remains to prove (A.153). (A.164) implies (A.167). $(maxpt(f_D(v'_t)), t_{last}]$ is either a period or the empty set (if $maxpt(f_D(v'_t)) = t_{last}$). It cannot be the empty set, because according to (A.167), $(maxpt(f_D(v'_t)), t_{last}]$ has $f_D(v_t)$ as its subset, and by (A.163) $f_D(v_t)$ is a period, i.e. a non-empty set. Hence, (A.168) holds. (A.167), (A.163), and (A.168) imply (A.169). (A.153) follows from (A.169) and (A.158). The forward direction of clause 3 has been proven.

$$(A.167) \quad f_D(v_t) \subseteq (maxpt(f_D(v'_t)), t_{last}]$$

$$(A.168) \quad (maxpt(f_D(v'_t)), t_{last}] \in PERIODS$$

$$(A.169) \quad f_D(v_t) \sqsubseteq (maxpt(f_D(v'_t)), t_{last}]$$

I now prove the backwards direction of clause 3. I assume that (A.147) – (A.154) hold. I need to prove that $\langle v, v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$. According to (A.146), it is enough to prove that for some v'_t , (A.155) – (A.157) hold. I set v'_t to v as required by (A.157), and prove (A.155) and (A.156). According to clause 3', in order to prove (A.155), it is enough to prove that:

$$(A.170) \quad g \in G$$

$$(A.171) \quad \|\tau_1\|^{M(st), g} = f_D(v_1), \dots, \|\tau_n\|^{M(st), g} = f_D(v_n)$$

$$(A.172) \quad \|\phi'\|^{M(st), st, f_D(v'_t), PTS, g} = T$$

(A.170) and (A.171) are the same as (A.147) and (A.150), which were assumed to hold. (A.157) (that holds), (A.149) and (A.151) imply (A.173). (A.173) and (A.154) imply (A.172). Hence, (A.155) holds.

$$(A.173) \quad f_D(v'_t) = et'$$

It remains to prove (A.156). (A.152) implies (A.174) and (A.175).

$$(A.174) \quad f_D(v_t) \in PERIODS$$

$$(A.175) \quad f_D(eval(st, \lambda, g^{db})) \in PERIODS$$

(A.174), (A.148), and (A.153) imply (A.176) and (A.177). (A.152) implies (A.178). (A.177) and (A.178) imply (A.179)

$$\begin{aligned}
 (A.176) \quad & (maxpt(et'), t_{last}] \in PERIODS \\
 (A.177) \quad & f_D(v_t) \subseteq f_D(eval(st, \lambda, g^{db})) \\
 (A.178) \quad & f_D(v_t) \subseteq (maxpt(et'), t_{last}] \\
 (A.179) \quad & f_D(v_t) \subseteq f_D(eval(st, \lambda, g^{db})) \cap (maxpt(et'), t_{last}]
 \end{aligned}$$

According to (A.175) and (A.176), $f_D(eval(st, \lambda, g^{db})) \cap (maxpt(et'), t_{last}]$ is the intersection of two periods. The intersection of two periods is the empty set if the periods do not overlap, or a period (the overlap of the two periods) if the periods overlap. $f_D(eval(st, \lambda, g^{db}))$ and $(maxpt(et'), t_{last}]$ do overlap, because according to (A.179), their intersection has $f_D(v_t)$ as its subset, and by (A.174) $f_D(v_t)$ is a period, i.e. a non-empty set. Hence, $f_D(eval(st, \lambda, g^{db})) \cap (maxpt(et'), t_{last}]$ is a period. This conclusion, (A.174), (A.179), and (A.173) imply (A.156). The backwards direction of clause 3 has been proven.

A.3.7 $Ntense[\beta, \phi']$

Translation rule

If $\beta \in VARS$, $\phi' \in YNFORMS$, and λ is a TSQL2 value expression, then:

$$\begin{aligned}
 trans(Ntense[\beta, \phi'], \lambda) & \stackrel{def}{=} \\
 & (SELECT DISTINCT VALID(\alpha), \alpha.1, \alpha.2, \dots, \alpha.n \\
 & \quad VALID PERIOD(TIMESTAMP 'beginning', TIMESTAMP 'forever') \\
 & \quad FROM trans(\phi', \lambda_{init}) AS \alpha \\
 &) (SUBPERIOD)
 \end{aligned}$$

λ_{init} is as in section 5.10, and n is the length of $\lceil \phi' \rceil$. Each time the translation rule is used, α is a new correlation name, obtained by calling the correlation names generator.

Proof that theorem 5.2 holds for $\phi = Ntense[\beta, \phi']$, if it holds for $\phi = \phi'$

The proof is very similar to that of section A.3.6.

A.3.8 $Ntense[now^*, \phi']$

Translation rule

If $\phi' \in YNFORMS$ and λ is a TSQL2 value expression, then:

$$\begin{aligned}
 trans(Ntense[now^*, \phi'], \lambda) & \stackrel{def}{=} \\
 & (SELECT DISTINCT \alpha.1, \alpha.2, \dots, \alpha.n \\
 & \quad VALID PERIOD(TIMESTAMP 'beginning', TIMESTAMP 'forever') \\
 & \quad FROM trans(\phi', \lambda_{init}) AS \alpha \\
 & \quad WHERE VALID(\alpha) = PERIOD(TIMESTAMP 'now', TIMESTAMP 'now')
 \end{aligned}$$

) (SUBPERIOD)

λ_{init} is as in section 5.10, and n is the length of $\lceil \phi' \rceil$. Each time the translation rule is used, α is a new correlation name, obtained by calling the correlation names generator.

Proof that theorem 5.2 holds for $\phi = Ntense[now^*, \phi']$, if it holds for $\phi = \phi'$

The proof is very similar to that of section A.3.6.

A.3.9 $For[\sigma_c, \nu_{qty}, \phi']$

Translation rule

If $\sigma_c \in CPARTS$, $\nu_{qty} \in \{1, 2, 3, \dots\}$, $\phi' \in YNFORMS$, and λ is a TSQL2 value expression, then:

$$\begin{aligned} trans(For[\sigma_c, \nu_{qty}, \phi'], \lambda) &\stackrel{def}{=} \\ &(\text{SELECT DISTINCT } \alpha.1, \alpha.2, \dots, \alpha.n \\ &\quad \text{VALID VALID}(\alpha) \\ &\quad \text{FROM } trans(\phi', \lambda) \text{ AS } \alpha \\ &\quad \text{WHERE INTERVAL}(\text{VALID}(\alpha), \gamma) = \text{INTERVAL } \nu_{qty} \gamma) \end{aligned}$$

n is the length of $\lceil \phi' \rceil$, and γ is the first element of the pair $h'_{cparts}(\sigma_c) = \langle \gamma, \Sigma_c \rangle$ (section 5.9). Each time the translation rule is used, α is a new correlation name, obtained by calling the correlation names generator.

Proof that theorem 5.2 holds for $\phi = For[\sigma_c, \nu_{qty}, \phi']$, if it holds for $\phi = \phi'$

I assume that $\sigma_c \in CPARTS$, $\nu_{qty} \in \{1, 2, 3, \dots\}$, and $\phi' \in YNFORMS$. By the syntax of TOP, this implies that $For[\sigma_c, \nu_{qty}, \phi'] \in YNFORMS$. I also assume that $st \in PTS$, λ is a TSQL2 value expression, $g^{db} \in G^{db}$, $eval(st, \lambda, g^{db}) \in D_P^*$, $\lceil \phi' \rceil = \langle \tau_1, \tau_2, \tau_3, \dots, \tau_n \rangle$, $h'_{cparts}(\sigma_c) = \langle \gamma, \Sigma_c \rangle$ (as in the translation rule), and $\Sigma = trans(For[\sigma_c, \nu_{qty}, \phi'], \lambda)$. From the definition of $\lceil \dots \rceil$, it should be easy to see that $\lceil For[\sigma_c, \nu_{qty}, \phi'] \rceil = \lceil \phi' \rceil = \langle \tau_1, \dots, \tau_n \rangle$. Finally, I assume that theorem 5.2 holds for $\phi = \phi'$. I need to show that:

1. $FCN(\Sigma) \subseteq FCN(\lambda)$
2. $eval(st, \Sigma, g^{db}) \in VREL_P(n)$
3. $\langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$ iff for some $g \in G$:
 $\|\tau_1\|^{M(st), g} = f_D(v_1), \dots, \|\tau_n\|^{M(st), g} = f_D(v_n)$, and
 $\|For[\sigma_c, \nu_{qty}, \phi']\|^{M(st), st, f_D(v_t), f_D(eval(st, \lambda, g^{db}))}, g} = T$

Let Σ' be the embedded SELECT statement in the FROM clause of Σ , i.e. $\Sigma' = trans(\phi', \lambda)$. From the hypothesis, $\phi' \in YNFORMS$, $st \in PTS$, $\lceil \phi' \rceil = \langle \tau_1, \dots, \tau_n \rangle$, λ is a value expression, $g^{db} \in G^{db}$, and $eval(st, \lambda, g^{db}) \in D_P^*$. Then, from theorem 5.2 for $\phi = \phi'$ (according to the hypothesis, theorem 5.2 holds for $\phi = \phi'$) we get:

- 1'. $FCN(\Sigma') \subseteq FCN(\lambda)$
- 2'. $eval(st, \Sigma', g^{db}) \in VREL_P(n)$
- 3'. $\langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma', g^{db})$ iff for some $g \in G$:
 $\|\tau_1\|^{M(st),g} = f_D(v_1), \dots, \|\tau_n\|^{M(st),g} = f_D(v_n)$, and
 $\|\phi'\|^{M(st),st,f_D(v_t),f_D(eval(st,\lambda,g^{db})),g} = T$

Proof of clause 1

The two $VALID(\alpha)$ in the $VALID$ and $WHERE$ clauses of Σ are not free column references in Σ , because Σ is a binding context for both of them. The $\alpha.1, \dots, \alpha.n$ in the $SELECT$ clause of Σ are not free column references in Σ for the same reason. Σ contains no other column references (and hence no other free column references), apart from those that possibly appear within Σ' . By lemma A.1, this implies (A.180). (A.180) and clause 1' imply clause 1.

$$(A.180) \quad FCN(\Sigma) \subseteq FCN(\Sigma')$$

Proof of clause 2

When computing $eval(st, \Sigma, g^{db})$, the α of Σ ranges over the tuples of $eval(st, \Sigma', g^{db})$. By clause 2', $eval(st, \Sigma', g^{db}) \in VREL_P(n)$. Hence, α ranges over tuples of the form $\langle v_1, \dots, v_n; v_t \rangle$, where $f_D(v_t) \in PERIODS$. The $VALID(\alpha)$ in the $WHERE$ clause of Σ stands for $f_D(v_t)$. The arrangements of sections 5.8 and 5.9 imply that γ is the name of the TSQL2 granularity that corresponds to the complete partitioning $f_{cparts}(st)(\sigma_c)$. Then, from the semantics of the $INTERVAL$ function (section 5.3.4), it should be easy to see that the constraint $INTERVAL(VALID(\alpha), \gamma) = INTERVAL \text{ '}\nu_{qty}\text{' } \gamma$ in the $WHERE$ clause of Σ is satisfied iff $f_D(v_t)$ covers exactly ν_{qty} consecutive periods from $f_{cparts}(st)(\sigma_c)$. It should now be easy to see from the translation rule that (A.181) holds.

$$(A.181) \quad eval(st, \Sigma, g^{db}) = \{ \langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma', g^{db}) \mid$$

$$\text{for some } p_1, p_2, \dots, p_{\nu_{qty}} \in f_{cparts}(st)(\sigma_c) :$$

$$\begin{aligned} &minpt(p_1) = minpt(f_D(v_t)), \text{ next(maxpt}(p_1)) = minpt(p_2), \\ &next(maxpt(p_2)) = minpt(p_3), \dots, next(maxpt(p_{\nu_{qty}-1})) = minpt(p_{\nu_{qty}}), \\ &\text{and } maxpt(p_{\nu_{qty}}) = maxpt(f_D(v_t)) \} \end{aligned}$$

Clause 2' and (A.181) imply that for every $\langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$, $v_t \in DP$. (A.181) also implies that $eval(st, \Sigma, g^{db})$ is a valid-time relation of n explicit attributes. Hence, $eval(st, \Sigma, g^{db}) \in VREL_P(n)$. Clause 2 has been proven.

Proof of clause 3

Using the definition of $\|For[\sigma_c, \nu_{qty}, \phi']\|^{st, et, lt, g}$ (section 3.14), clause 3 becomes:

$$\begin{aligned}
 & \langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db}) \text{ iff for some } g \text{ and } p_1, p_2, \dots, p_{\nu_{qty}} : \\
 (A.182) \quad & g \in G \\
 (A.183) \quad & \|\tau_1\|^{M(st), g} = f_D(v_1), \dots, \|\tau_n\|^{M(st), g} = f_D(v_n) \\
 (A.184) \quad & \|\phi'\|^{M(st), st, f_D(v_t), f_D(eval(st, \lambda, g^{db})), g} = T \\
 (A.185) \quad & p_1, \dots, p_{\nu_{qty}} \in f_{cparts}(st)(\sigma_c) \\
 (A.186) \quad & minpt(p_1) = minpt(f_D(v_t)), next(maxpt(p_1)) = minpt(p_2), \\
 & next(maxpt(p_2)) = minpt(p_3), \dots, next(maxpt(p_{\nu_{qty}-1})) = minpt(p_{\nu_{qty}}), \\
 & \text{and } maxpt(p_{\nu_{qty}}) = maxpt(f_D(v_t))
 \end{aligned}$$

I first prove that the forward direction of clause 3 holds. I assume that $\langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$. I need to prove that for some $g, p_1, \dots, p_{\nu_{qty}}$, (A.182) – (A.186) hold. The assumption that $\langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$, and (A.181) imply that for some $p_1, \dots, p_{\nu_{qty}}$:

$$\begin{aligned}
 (A.187) \quad & \langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma', g^{db}) \\
 (A.188) \quad & p_1, \dots, p_{\nu_{qty}} \in f_{cparts}(st)(\sigma_c) \\
 (A.189) \quad & minpt(p_1) = minpt(f_D(v_t)), next(maxpt(p_1)) = minpt(p_2), \\
 & next(maxpt(p_2)) = minpt(p_3), \dots, next(maxpt(p_{\nu_{qty}-1})) = minpt(p_{\nu_{qty}}), \\
 & \text{and } maxpt(p_{\nu_{qty}}) = maxpt(f_D(v_t))
 \end{aligned}$$

(A.187) and clause 3' imply that for some g :

$$\begin{aligned}
 (A.190) \quad & g \in G \\
 (A.191) \quad & \|\tau_1\|^{M(st), g} = f_D(v_1), \dots, \|\tau_n\|^{M(st), g} = f_D(v_n) \\
 (A.192) \quad & \|\phi'\|^{M(st), st, f_D(v_t), f_D(eval(st, \lambda, g^{db})), g} = T
 \end{aligned}$$

(A.182), (A.183), (A.184), (A.185), and (A.186), are the same as (A.190), (A.191), (A.192), (A.188) and (A.189) respectively, which are known to be true. The forward direction of clause 3 has been proven

I now prove the backwards direction of clause 3. I assume that (A.182) – (A.186) hold. I need to prove that $\langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$. According to (A.181), it is enough to prove that (A.187) – (A.189) hold. (A.188) and (A.189) are the same as (A.185) and (A.186) respectively, which were assumed to hold. (A.187) follows from clause 3' and (A.182), (A.183), and (A.184). The backwards direction of clause 3 has been proven.

A.3.10 Begin[ϕ']**Translation rule**

If $\phi' \in YNFORMS$ and λ is a TSQL2 value expression, then:

$trans(Begin[\phi'], \lambda) \stackrel{def}{=} \\
(\text{SELECT DISTINCT } \alpha.1, \alpha.2, \dots, \alpha.n \\
\text{VALID PERIOD}(\text{BEGIN}(\text{VALID}(\alpha)), \text{BEGIN}(\text{VALID}(\alpha))) \\
\text{FROM } trans(\phi', \lambda_{init})(\text{NOSUBPERIOD}) \text{ AS } \alpha \\
\text{WHERE } \lambda \text{ CONTAINS } \text{BEGIN}(\text{VALID}(\alpha)))$

n is the length of $\lceil \phi' \rceil$, and λ_{init} is as in section 5.10. Each time the translation rule is used, α is a new correlation name, obtained by calling the correlation names generator after λ has been supplied.

Proof that theorem 5.2 holds for $\phi = Begin[\phi']$, if it holds for $\phi = \phi'$

I assume that $\phi' \in YNFORMS$. By the syntax of TOP, this implies that $Begin[\phi'] \in YNFORMS$. I also assume that $st \in PTS$, λ is a TSQL2 value expression, λ_{init} is as in section 5.10, $g^{db} \in G^{db}$, $eval(st, \lambda, g^{db}) \in D_P^*$, $\lceil \phi' \rceil = \langle \tau_1, \tau_2, \tau_3, \dots, \tau_n \rangle$, and $\Sigma = trans(Begin[\phi'], \lambda)$. From the definition of $\lceil \dots \rceil$, it should be easy to see that $\lceil Begin[\phi'] \rceil = \lceil \phi' \rceil = \langle \tau_1, \dots, \tau_n \rangle$. Finally, I assume that theorem 5.2 holds for $\phi = \phi'$. I need to show that:

1. $FCN(\Sigma) \subseteq FCN(\lambda)$
2. $eval(st, \Sigma, g^{db}) \in VREL_P(n)$
3. $\langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$ iff for some $g \in G$:
 $\|\tau_1\|^{M(st),g} = f_D(v_1), \dots, \|\tau_n\|^{M(st),g} = f_D(v_n)$, and
 $\|Begin[\phi']\|^{M(st),st,f_D(v_t),f_D(eval(st,\lambda,g^{db})),g} = T$

According to the syntax of TSQL2, λ_{init} is a value expression. By lemma 5.1, (A.193) – (A.195) hold.

$$(A.193) \quad f_D(eval(st, \lambda_{init}, g^{db})) = PTS$$

$$(A.194) \quad eval(st, \lambda_{init}, g^{db}) \in D_P^*$$

$$(A.195) \quad FCN(\lambda_{init}) = \emptyset$$

Let Σ' be the SELECT statement in the FROM clause of Σ , i.e. $\Sigma' = trans(\phi', \lambda_{init})$. From the hypothesis, $\phi' \in YNFORMS$, $st \in PTS$, $\lceil \phi' \rceil = \langle \tau_1, \dots, \tau_n \rangle$, and $g^{db} \in G^{db}$. From the discussion above, λ_{init} is a TSQL2 value expression, and $eval(st, \lambda_{init}, g^{db}) \in D_P^*$. Then, from theorem 5.2 for $\phi = \phi'$ (according to the hypothesis, theorem 5.2 holds for $\phi = \phi'$), and using (A.193) and (A.195), we get:

$$1'. \quad FCN(\Sigma') \subseteq \emptyset$$

$$2'. \quad eval(st, \Sigma', g^{db}) \in VREL_P(n)$$

$$3'. \quad \langle v_1, \dots, v_n; v'_t \rangle \in eval(st, \Sigma', g^{db}) \text{ iff for some } g \in G: \\
\|\tau_1\|^{M(st),g} = f_D(v_1), \dots, \|\tau_n\|^{M(st),g} = f_D(v_n), \text{ and} \\
\|\phi'\|^{M(st),st,f_D(v'_t),PTS,g} = T$$

Proof of clause 1

The three $\text{VALID}(\alpha)$ in the VALID and WHERE clauses of Σ are not free column references in Σ , because Σ is a binding context for all of them. The $\alpha.1, \dots, \alpha.n$ in the SELECT clause of Σ are not free column references in Σ for the same reason. Σ contains no other column references (and hence no other free column references), apart from those that possibly appear within Σ' or the λ in the WHERE clause of Σ . By lemma A.1, this implies (A.196). Clause 1' and (A.196) imply clause 1.

$$(A.196) \quad FCN(\Sigma) \subseteq FCN(\Sigma') \cup FCN(\lambda)$$

Proof of clause 2

When computing $\text{eval}(st, \Sigma, g^{db})$, the α of Σ ranges over the tuples of the relation $\text{nosubperiod}(\text{eval}(st, \Sigma', g^{db}))$. By clause 2', $\text{eval}(st, \Sigma', g^{db}) \in \text{VREL}_P(n)$. From the definition of nosubperiod (section 5.3.2), it follows that $\text{nosubperiod}(\text{eval}(st, \Sigma', g^{db}))$ is also a valid-time relation of n explicit attributes, and that its time-stamps are also time-stamps of $\text{eval}(st, \Sigma', g^{db})$, i.e. elements of D_P . Hence, $\text{nosubperiod}(\text{eval}(st, \Sigma', g^{db})) \in \text{VREL}_P(n)$.

α is generated by calling the correlation names generator after λ has been supplied. Hence, α cannot appear in λ . The fact that α does not appear in λ means that for every tuple $\langle v_1, \dots, v_n; v'_t \rangle$:

$$(A.197) \quad \text{eval}(st, \lambda, (g^{db})_{\langle v_1, \dots, v_n; v'_t \rangle}^\alpha) = \text{eval}(st, \lambda, g^{db})$$

The reader should now be able to see from the translation rule that (A.198) holds. Intuitively, $\langle v_1, \dots, v_n; v'_t \rangle$ is the tuple of $\text{nosubperiod}(\text{eval}(st, \Sigma', g^{db}))$ to which α refers. I should have used $\text{eval}(st, \lambda, (g^{db})_{\langle v_1, \dots, v_n; v'_t \rangle}^\alpha)$ instead of $\text{eval}(st, \lambda, g^{db})$, to capture the fact that if there are any free column references of α in λ , these have to be taken to refer to the $\langle v_1, \dots, v_n; v'_t \rangle$ tuple to which α refers. By (A.197), however, $\text{eval}(st, \lambda, (g^{db})_{\langle v_1, \dots, v_n; v'_t \rangle}^\alpha)$ is the same as $\text{eval}(st, \lambda, g^{db})$.

$$(A.198) \quad \begin{aligned} \text{eval}(st, \Sigma, g^{db}) &= \{ \langle v_1, \dots, v_n; v_t \rangle \mid \text{for some } v'_t, \\ &\quad \langle v_1, \dots, v_n; v'_t \rangle \in \text{nosubperiod}(\text{eval}(st, \Sigma', g^{db})), \\ &\quad f_D(v_t) = \{\text{minpt}(f_D(v'_t))\}, \text{ and} \\ &\quad \text{minpt}(f_D(v'_t)) \in f_D(\text{eval}(st, \lambda, g^{db})) \} \end{aligned}$$

Using the definition of nosubperiod (section 5.3.2), (A.198) becomes (A.199).

$$(A.199) \quad \begin{aligned} \text{eval}(st, \Sigma, g^{db}) &= \{ \langle v_1, \dots, v_n; v_t \rangle \mid \text{for some } v'_t, \\ &\quad \langle v_1, \dots, v_n; v'_t \rangle \in \text{eval}(st, \Sigma', g^{db}), \\ &\quad \text{there is no } \langle v_1, \dots, v_n; v''_t \rangle \in \text{eval}(st, \Sigma', g^{db}) \\ &\quad \quad \text{such that } f_D(v'_t) \sqsubset f_D(v''_t), \\ &\quad f_D(v_t) = \{\text{minpt}(f_D(v'_t))\}, \text{ and} \\ &\quad \text{minpt}(f_D(v'_t)) \in f_D(\text{eval}(st, \lambda, g^{db})) \} \end{aligned}$$

(A.199) implies that every time-stamp v_t of $eval(st, \Sigma, g^{db})$ represents an (instantaneous) period that contains only the earliest chronon of a time-stamp of $eval(st, \Sigma', g^{db})$. This implies that $v_t \in D_P$. (A.199) also implies that $eval(st, \Sigma, g^{db})$ is a valid-time relation of n explicit attributes. Hence, $eval(st, \Sigma, g^{db}) \in VREL_P(n)$, and clause 2 has been proven.

Proof of clause 3

Using the definition of $\|Begin[\phi']\|^{M(st),st,et,lt,g}$ (section 3.12), clause 3 becomes:¹

$$\begin{aligned}
 & \langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db}) \text{ iff for some } g \text{ and } et' : \\
 \text{(A.200)} \quad & g \in G \\
 \text{(A.201)} \quad & \|\tau_1\|^{M(st),g} = f_D(v_1), \dots, \|\tau_n\|^{M(st),g} = f_D(v_n) \\
 \text{(A.202)} \quad & f_D(v_t) \sqsubseteq f_D(eval(st, \lambda, g^{db})) \\
 \text{(A.203)} \quad & f_D(v_t) = \{minpt(et')\} \\
 \text{(A.204)} \quad & et' \in mxlpers(\{e \in PERIODS \mid \|\phi\|^{M(st),st,e,PTS,g} = T\})
 \end{aligned}$$

I first prove that the forward direction of clause 3 holds. I assume that $\langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$. I need to prove that for some g and et' , (A.200) – (A.204) hold. The assumption that $\langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$, and (A.199) imply that for some v'_t :

$$\begin{aligned}
 \text{(A.205)} \quad & \langle v_1, \dots, v_n; v'_t \rangle \in eval(st, \Sigma', g^{db}) \\
 \text{(A.206)} \quad & \text{there is no } \langle v_1, \dots, v_n; v''_t \rangle \in eval(st, \Sigma', g^{db}) \\
 & \text{such that } f_D(v'_t) \sqsubset f_D(v''_t) \\
 \text{(A.207)} \quad & f_D(v_t) = \{minpt(f_D(v'_t))\} \\
 \text{(A.208)} \quad & minpt(f_D(v'_t)) \in f_D(eval(st, \lambda, g^{db}))
 \end{aligned}$$

(A.205) and clause 3' imply that for some g :

$$\begin{aligned}
 \text{(A.209)} \quad & g \in G \\
 \text{(A.210)} \quad & \|\tau_1\|^{M(st),g} = f_D(v_1), \dots, \|\tau_n\|^{M(st),g} = f_D(v_n) \\
 \text{(A.211)} \quad & \|\phi'\|^{M(st),st,f_D(v'_t),PTS,g} = T
 \end{aligned}$$

I set et' as in (A.212) and prove that (A.200) – (A.204) hold. (A.200) and (A.201) are the same as (A.209) and (A.210), which are known to hold. (A.203) follows from (A.207) and (A.212).

$$\text{(A.212)} \quad et' = f_D(v'_t)$$

I now prove (A.202). According to (A.205), v'_t is a time-stamp of $eval(st, \Sigma', g^{db})$, and by clause 2', $eval(st, \Sigma', g^{db}) \in VREL_P(n)$. This implies that $v'_t \in D_P$, which in turn

¹ The reader is reminded that the *mxlpers* symbol is overloaded. When $l \in TELEMS$, *mxlpers*(l) is the set of the maximal periods of a *temporal element*, and it is defined as in section 5.2.2. When S is a set of periods, *mxlpers*(S) is the set of the maximal periods of a *set of periods*, and it is defined as in section 3.3.

implies (A.213). By (A.207), $f_D(v_t)$ is the instantaneous period that contains only the first chronon of $f_D(v'_t)$. Therefore, (A.214) also holds.

$$(A.213) \quad f_D(v'_t) \in PERIODS$$

$$(A.214) \quad f_D(v_t) \in PERIODS$$

From the hypothesis, $eval(st, \lambda, g^{db}) \in D_P^*$, which implies that $f_D(eval(st, \lambda, g^{db}))$ is a period or the empty set. (A.208) implies that $f_D(eval(st, \lambda, g^{db}))$ is not the empty set. Therefore, (A.215) holds. (A.208) implies (A.216). (A.216), (A.207), (A.214), and (A.215) imply (A.202).

$$(A.215) \quad f_D(eval(st, \lambda, g^{db})) \in PERIODS$$

$$(A.216) \quad \{minpt(f_D(v'_t))\} \subseteq f_D(eval(st, \lambda, g^{db}))$$

It remains to prove (A.204). (A.212), (A.213), and (A.211) imply that:

$$(A.217) \quad et' \in \{e \in PERIODS \mid \|\phi'\|^{M(st), st, e, PTS, g} = T\}$$

To prove (A.204), I need to prove that there is no et'' that satisfies both (A.218) and (A.219).

$$(A.218) \quad et'' \in \{e \in PERIODS \mid \|\phi'\|^{M(st), st, e, PTS, g} = T\}$$

$$(A.219) \quad et' \sqsubset et''$$

Let us assume that for some et'' , (A.218) and (A.219) hold. (A.218) implies that:

$$(A.220) \quad \|\phi'\|^{M(st), st, et'', PTS, g} = T$$

$$(A.221) \quad et'' \in PERIODS$$

I set $v_t'' = f_D^{-1}(et'')$, which implies (A.222). (A.209), (A.210), (A.222), (A.220), and clause 3' imply (A.223). (A.219), (A.212), and (A.222) imply (A.224).

$$(A.222) \quad et'' = f_D(v_t'')$$

$$(A.223) \quad \langle v_1, \dots, v_n; v_t'' \rangle \in eval(st, \Sigma', g^{db})$$

$$(A.224) \quad f_D(v_t'') \sqsubset f_D(v_t')$$

(A.223) and (A.224) are against (A.206). Therefore, there can be no et'' that satisfies (A.218) and (A.219). (A.204) and the forward direction of clause 3 have been proven.

I now prove the backwards direction of clause 3. I assume that for some g and et' , (A.200) – (A.204) hold. I need to prove that $\langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$. According to (A.199), it is enough to prove that for some v'_t , (A.205) – (A.208) hold.

(A.204) implies (A.225). I set $v'_t = f_D^{-1}(et')$, which implies (A.226). (A.200), (A.201), (A.226), (A.225), and clause 3' imply (A.205). (A.207) follows from (A.203) and (A.226).

$$(A.225) \quad \|\phi\|^{M(st), st, et', PTS, g} = T$$

$$(A.226) \quad et' = f_D(v'_t)$$

I now prove (A.208). (A.202) and (A.203) imply (A.227). (A.227) and (A.226) imply (A.208).

$$(A.227) \quad \text{minpt}(et') \in f_D(\text{eval}(st, \lambda, g^{db}))$$

It remains to prove (A.206). Let us assume that there is a tuple $\langle v_1, \dots, v_n; v_t'' \rangle$, such that (A.228) – (A.229) hold.

$$(A.228) \quad \langle v_1, \dots, v_n; v_t'' \rangle \in \text{eval}(st, \Sigma', g^{db})$$

$$(A.229) \quad f_D(v_t') \sqsubset f_D(v_t'')$$

(A.228) and clause 3' imply that for some g' :

$$(A.230) \quad g' \in G$$

$$(A.231) \quad \|\tau_1\|^{M(st), g'} = f_D(v_1), \dots, \|\tau_n\|^{M(st), g'} = f_D(v_n)$$

$$(A.232) \quad \|\phi'\|^{M(st), st, f_D(v_t''), PTS, g'} = T$$

Lemma A.4, (A.200), (A.230), the assumptions that $\phi' \in \text{YNFORMS}$ and $\lceil \phi' \rceil = \langle \tau_1, \dots, \tau_n \rangle$, (A.201), and (A.231) imply that for every variable β in ϕ' , $g(\beta) = g'(\beta)$. Then, (A.233) holds. (A.232) and (A.233) imply (A.234).

$$(A.233) \quad \|\phi'\|^{M(st), st, f_D(v_t''), PTS, g'} = \|\phi'\|^{M(st), st, f_D(v_t''), PTS, g}$$

$$(A.234) \quad \|\phi'\|^{M(st), st, f_D(v_t''), PTS, g} = T$$

I set et'' as in (A.235). (A.229), (A.226), and (A.235) imply (A.236). (A.234) and (A.235) imply (A.237).

$$(A.235) \quad et'' = f_D(v_t'')$$

$$(A.236) \quad et' \sqsubset et''$$

$$(A.237) \quad \|\phi'\|^{M(st), st, et'', PTS, g} = T$$

(A.236), and (A.237) are against (A.204), because (A.204) and the definition of *mxlpers* (see section 3.3) imply that there is no $et'' \in \text{PERIODS}$, such that $et' \sqsubset et''$ and $\|\phi'\|^{M(st), st, et'', PTS, g} = T$. Therefore, there can be no tuple $\langle v_1, \dots, v_n; v_t'' \rangle$ such that (A.228) and (A.229) hold. (A.206) and the backwards direction of clause 3 have been proven.

A.3.11 $\text{End}[\phi']$

Translation rule

If $\phi' \in \text{YNFORMS}$ and λ is a TSQL2 value expression, then:

$$\text{trans}(\text{End}[\phi'], \lambda) \stackrel{\text{def}}{=} \\ \begin{aligned} &(\text{SELECT DISTINCT } \alpha.1, \alpha.2, \dots, \alpha.n \\ &\quad \text{VALID PERIOD}(\text{END}(\text{VALID}(\alpha)), \text{END}(\text{VALID}(\alpha))) \\ &\quad \text{FROM } \text{trans}(\phi', \lambda_{init})(\text{NOSUBPERIOD}) \text{ AS } \alpha \\ &\quad \text{WHERE } \lambda \text{ CONTAINS } \text{END}(\text{VALID}(\alpha))) \end{aligned}$$

n is the length of $\lceil \phi' \rceil$, and λ_{init} is as in section 5.10. Each time the translation rule is used, α is a new correlation name, obtained by calling the correlation names generator after λ has been supplied.

Proof that theorem 5.2 holds for $\phi = \text{End}[\phi']$, if it holds for $\phi = \phi'$

The proof is very similar to that of section A.3.10.

A.3.12 $\text{At}[\kappa, \phi']$

Translation rule

If $\kappa \in \text{CONS}$, $\phi' \in \text{YNFORMS}$, and λ is a TSQL2 value expression, then:

$$\text{trans}(\text{At}[\kappa, \phi'], \lambda) \stackrel{\text{def}}{=} \text{trans}(\phi', \lambda')$$

where λ' is the expression $\text{INTERSECT}(\lambda, h'_{\text{cons}}(\kappa))$.

Proof that theorem 5.2 holds for $\phi = \text{At}[\kappa, \phi']$, if it holds for $\phi = \phi'$

I assume that $\kappa \in \text{CONS}$ and $\phi' \in \text{YNFORMS}$. By the syntax of TOP, this implies that $\text{At}[\kappa, \phi'] \in \text{YNFORMS}$. I also assume that $st \in \text{PTS}$, λ is a TSQL2 value expression, λ' is as in the translation rule, $g^{db} \in G^{db}$, $\text{eval}(st, \lambda, g^{db}) \in D_P^*$, $\ulcorner \phi' \urcorner = \langle \tau_1, \tau_2, \tau_3, \dots, \tau_n \rangle$, and $\Sigma = \text{trans}(\text{At}[\kappa, \phi'], \lambda)$. From the definition of $\ulcorner \dots \urcorner$, it should be easy to see that $\ulcorner \text{At}[\kappa, \phi'] \urcorner = \ulcorner \phi' \urcorner = \langle \tau_1, \dots, \tau_n \rangle$. Finally, I assume that theorem 5.2 holds for $\phi = \phi'$. I need to show that:

1. $\text{FCN}(\Sigma) \subseteq \text{FCN}(\lambda)$
2. $\text{eval}(st, \Sigma, g^{db}) \in \text{VREL}_P(n)$
3. $\langle v_1, \dots, v_n; v_t \rangle \in \text{eval}(st, \Sigma, g^{db})$ iff for some $g \in G$:
 $\|\tau_1\|^{M(st), g} = f_D(v_1), \dots, \|\tau_n\|^{M(st), g} = f_D(v_n)$, and
 $\|\text{At}[\kappa, \phi']\|^{M(st), st, f_D(v_t), f_D(\text{eval}(st, \lambda, g^{db}))}, g} = T$

The restrictions of section 5.5 guarantee (A.238). By the definitions of f_{cons} and h_{cons} of sections 5.8 and 5.9, (A.239) holds and (A.238) is equivalent to (A.240). (I do not include the assignment to the correlation names among the arguments of eval , because by section 5.9, $\text{FCN}(h'_{\text{cons}}(\kappa)) = \emptyset$.)

$$(A.238) \quad f_{\text{cons}}(st)(\kappa) \in \text{PERIODS}$$

$$(A.239) \quad f_{\text{cons}}(st)(\kappa) = f_D(\text{eval}(st, h'_{\text{cons}}(\kappa)))$$

$$(A.240) \quad f_D(\text{eval}(st, h'_{\text{cons}}(\kappa))) \in \text{PERIODS}$$

By the syntax of TSQL2, since λ is a value expression, λ' is also a value expression. From the definition of λ' it should be obvious that any free column reference in λ' is situated within the λ of λ' . By lemma A.1, this implies (A.241).

$$(A.241) \quad \text{FCN}(\lambda') \subseteq \text{FCN}(\lambda)$$

The assumption that $eval(st, \lambda, g^{db}) \in D_P^*$, (A.240), and the definition of λ' imply (A.242) and that $eval(st, \lambda', g^{db}) \in D_P^*$.

$$(A.242) \quad f_D(eval(st, \lambda', g^{db})) = f_D(eval(st, \lambda, g^{db})) \cap f_D(eval(st, h'_{cons}(\kappa)))$$

The hypothesis that $\Sigma = trans(At[\kappa, \phi'], \lambda)$ and the translation rule of this section imply that $\Sigma = trans(\phi, \lambda')$. From the hypothesis, $\phi' \in YNFORMS$, $st \in PTS$, $\lceil \phi' \rceil = \langle \tau_1, \dots, \tau_n \rangle$, and $g^{db} \in G^{db}$. According to the discussion above, λ' is a value expression, and $eval(st, \lambda', g^{db}) \in D_P^*$. Then, from theorem 5.2 for $\phi = \phi'$ (according to the hypothesis, theorem 5.2 holds for $\phi = \phi'$) we get:

$$1'. FCN(\Sigma) \subseteq FCN(\lambda')$$

$$2'. eval(st, \Sigma, g^{db}) \in VREL_P(n)$$

$$3'. \langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db}) \text{ iff for some } g \in G: \\ \|\tau_1\|^{M(st),g} = f_D(v_1), \dots, \|\tau_n\|^{M(st),g} = f_D(v_n), \text{ and} \\ \|\phi'\|^{M(st),st,f_D(v_t),f_D(eval(st,\lambda',g^{db})),g} = T$$

Proofs of clauses 1 and 2

Clause 1 follows from clause 1' and (A.241). Clause 2 is the same as clause 2', which is known to hold.

Proof of clause 3

I prove clause 3 by proving (A.243). If (A.243) holds, then clause 3' is equivalent to clause 3, and since clause 3' holds, clause 3 holds too.

$$(A.243) \quad \|\phi'\|^{M(st),st,f_D(v_t),f_D(eval(st,\lambda',g^{db})),g} = T, \text{ iff} \\ \|At[\kappa, \phi']\|^{M(st),st,f_D(v_t),f_D(eval(st,\lambda,g^{db})),g} = T$$

From the hypothesis, $\kappa \in CONS$. By the semantics of TOP, this implies that:

$$(A.244) \quad \|\kappa\|^{M(st),g} = f_{cons}(st)(\kappa)$$

I first prove the forward direction of (A.243). I assume that (A.245) holds.

$$(A.245) \quad \|\phi'\|^{M(st),st,f_D(v_t),f_D(eval(st,\lambda',g^{db})),g} = T$$

Using (A.242) and (A.239), (A.245) becomes (A.246).

$$(A.246) \quad \|\phi'\|^{M(st),st,f_D(v_t),f_D(eval(st,\lambda,g^{db})) \cap f_{cons}(st)(\kappa),g} = T$$

Using (A.244), (A.246) and (A.238) become (A.247) and (A.248) respectively. (A.247), (A.248), and the definition of At (section 3.10) imply (A.249). The forward direction

of (A.243) has been proven.

$$(A.247) \quad \|\phi'\|^{M(st),st,f_D(v_t),f_D(eval(st,\lambda,g^{db}))\cap\|\kappa\|^{M(st),g},g} = T$$

$$(A.248) \quad \|\kappa\|^{M(st),g} \in PERIODS$$

$$(A.249) \quad \|At[\kappa, \phi']\|^{M(st),st,f_D(v_t),f_D(eval(st,\lambda,g^{db}))g} = T$$

I now prove the backwards direction of (A.243). I assume that (A.249) holds. By the definition of At , this implies that (A.247) holds. Using (A.244), (A.247) becomes (A.246). (A.239), (A.242), and (A.246) imply (A.245). The backwards direction of (A.243) has been proven.

A.3.13 *Before* $[\kappa, \phi']$

Translation rule

If $\kappa \in CONS$, $\phi' \in YNFORMS$, and λ is a TSQL2 value expression, then:

$$trans(Before[\kappa, \phi'], \lambda) \stackrel{def}{=} trans(\phi', \lambda')$$

where λ' is the expression:

`INTERSECT(λ , PERIOD(TIMESTAMP 'beginning', BEGIN($h'_{cons}(\kappa)$) - INTERVAL '1' χ))`

and χ is the TSQL2 name of the granularity of chronons.

Proof that theorem 5.2 holds for $\phi = Before[\kappa, \phi']$, if it holds for $\phi = \phi'$

The proof is very similar to that of section A.3.12.

A.3.14 *After* $[\kappa, \phi']$

Translation rule

If $\kappa \in CONS$, $\phi' \in YNFORMS$, and λ is a TSQL2 value expression, then:

$$trans(After[\kappa, \phi'], \lambda) \stackrel{def}{=} trans(\phi', \lambda')$$

where λ' is the expression:

`INTERSECT(λ , PERIOD(END($h'_{cons}(\kappa)$) + INTERVAL '1' χ , TIMESTAMP 'forever'))`

and χ is the TSQL2 name of the granularity of chronons.

Proof that theorem 5.2 holds for $\phi = After[\kappa, \phi']$, if it holds for $\phi = \phi'$

The proof is very similar to that of section A.3.12.

A.3.15 $At[\sigma_g, \beta, \phi']$ **Translation rule**

If $\sigma_g \in GPARTS$, $\beta \in VARS$, $\phi' \in YNFORMS$, and λ is a TSQL2 value expression, then:

$$\begin{aligned} trans(At[\sigma_g, \beta, \phi'], \lambda) &\stackrel{def}{=} \\ &(\text{SELECT DISTINCT } \alpha_1.1, \alpha_2.1, \alpha_2.2, \dots, \alpha_2.n \\ &\quad \text{VALID VALID}(\alpha_2) \\ &\quad \text{FROM } (h'_{gparts}(\sigma_g)) \text{ AS } \alpha_1, trans(\phi', \lambda') \text{ AS } \alpha_2) \end{aligned}$$

n is the length of $\lceil \phi' \rceil$, and λ' is the expression $\text{INTERSECT}(\alpha_1.1, \lambda)$ ² Each time the translation rule is used, α_1 and α_2 are two new different correlation names, obtained by calling the correlation names generator after λ has been supplied.

Proof that theorem 5.2 holds for $\phi = At[\sigma_g, \beta, \phi']$, if it holds for $\phi = \phi'$

I assume that $\sigma_g \in GPARTS$, $\beta \in VARS$, and $\phi' \in YNFORMS$. By the syntax of TOP, this implies that $At[\sigma_g, \beta, \phi'] \in YNFORMS$. I also assume that $st \in PTS$, λ is a TSQL2 value expression, λ' is as in the translation rule, $g^{db} \in G^{db}$, $eval(st, \lambda, g^{db}) \in D_P^*$, $\lceil \phi' \rceil = \langle \tau_1, \tau_2, \tau_3, \dots, \tau_n \rangle$, and $\Sigma = trans(At[\sigma_g, \beta, \phi'], \lambda)$. From the definition of $\lceil \dots \rceil$, it should be easy to see that $\lceil At[\sigma_g, \beta, \phi'] \rceil = \langle \beta, \tau_1, \dots, \tau_n \rangle$. Finally, I assume that theorem 5.2 holds for $\phi = \phi'$. I need to show that:

1. $FCN(\Sigma) \subseteq FCN(\lambda)$
2. $eval(st, \Sigma, g^{db}) \in VREL_P(n+1)$
3. $\langle v, v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$ iff for some $g \in G$:
 $\|\beta\|^{M(st),g} = f_D(v)$, $\|\tau_1\|^{M(st),g} = f_D(v_1)$, \dots , $\|\tau_n\|^{M(st),g} = f_D(v_n)$, and
 $\|At[\sigma_g, \beta, \phi']\|^{M(st),st,f_D(v_t),f_D(eval(st,\lambda,g^{db})),g} = T$

From the definition of λ' it should be obvious that any free column reference in λ' is either the $\alpha_1.1$ of λ' , or is situated within the λ of λ' . By lemma A.1, this implies (A.250). The only correlation name that has a free column reference in $\alpha_1.1$ is α_1 . Hence, $FCN(\alpha_1.1) = \{\alpha_1\}$, and (A.250) becomes (A.251).

$$(A.250) \quad FCN(\lambda') \subseteq FCN(\alpha_1.1) \cup FCN(\lambda)$$

$$(A.251) \quad FCN(\lambda') \subseteq \{\alpha_1\} \cup FCN(\lambda)$$

The α_1 of Σ is generated by calling the correlation names generator after λ has been supplied. Hence, α_1 cannot appear in λ . The fact that α_1 does not appear in λ means

² λ' will end up being a part of the embedded SELECT statement $trans(\phi', \lambda')$. This means that α_1 , which is part of λ' , will appear within $trans(\phi', \lambda')$, i.e. in the same FROM clause that defines α_1 . This is allowed in the TSQL2 version of this thesis; see section 5.3.5. Similar comments apply to the translation rules for $Before[\sigma_g, \beta, \phi']$, $After[\sigma_g, \beta, \phi']$, $At[\sigma_c, \beta, \phi']$, $Before[\sigma_c, \beta, \phi']$, and $After[\sigma_c, \beta, \phi']$.

that for every possible tuple $\langle v \rangle$ of a one-attribute snapshot relation (i.e. for every $v \in D$):

$$(A.252) \quad eval(st, \lambda, (g^{db})_{\langle v \rangle}^{\alpha_1}) = eval(st, \lambda, g^{db})$$

The assumption that $eval(st, \lambda, g^{db}) \in D_P^*$, and the fact that for every $v \in D$, (A.252) holds imply that (A.253) and (A.254) hold for every $v \in D$.

$$(A.253) \quad eval(st, \lambda, (g^{db})_{\langle v \rangle}^{\alpha_1}) \in D_P^*$$

$$(A.254) \quad f_D(eval(st, \lambda, (g^{db})_{\langle v \rangle}^{\alpha_1})) \in PERIODS^*$$

By the syntax of TOP, since λ is a value expression, λ' is also a value expression. If $v \in D_P$ ($D_P \subseteq D$), by (A.254) (which holds for $v \in D$) and the definition of λ' , (A.255) and (A.256) hold.

$$(A.255) \quad f_D(eval(st, \lambda', (g^{db})_{\langle v \rangle}^{\alpha_1})) = f_D(v) \cap f_D(eval(st, \lambda, (g^{db})_{\langle v \rangle}^{\alpha_1}))$$

$$(A.256) \quad eval(st, \lambda', (g^{db})_{\langle v \rangle}^{\alpha_1}) \in D_P^*$$

Let Σ' be the embedded SELECT statement in the FROM clause of Σ to which α_2 refers, i.e. $\Sigma' = trans(\phi', \lambda')$. From the hypothesis, $\phi' \in YNFORMS$, $st \in PTS$, $g^{db} \in G$, and $\ulcorner \phi' \urcorner = \langle \tau_1, \dots, \tau_n \rangle$. From the discussion above, λ' is a value expression. If $v \in D_P$, then $(g^{db})_{\langle v \rangle}^{\alpha_1} \in G^{db}$ and (by (A.256)) $eval(st, \lambda', (g^{db})_{\langle v \rangle}^{\alpha_1}) \in D_P^*$. From theorem 5.2 for $\phi = \phi'$ (according to the hypothesis, theorem 5.2 holds for $\phi = \phi'$) we get the following. (The condition $v \in D_P$ does not affect clause 1'.)

$$1'. FCN(\Sigma') \subseteq FCN(\lambda')$$

$$2'. \text{ If } v \in D_P, \text{ then } eval(st, \Sigma', (g^{db})_{\langle v \rangle}^{\alpha_1}) \in VREL_P(n)$$

$$3'. \text{ If } v \in D_P, \text{ then:}$$

$$\left(\begin{array}{l} \langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma', (g^{db})_{\langle v \rangle}^{\alpha_1}) \text{ iff for some } g' \in G: \\ \|\tau_1\|^{M(st), g'} = f_D(v_1), \dots, \|\tau_n\|^{M(st), g'} = f_D(v_n), \text{ and} \\ \|\phi'\|^{M(st), st, f_D(v_t), f_D(eval(st, \lambda', (g^{db})_{\langle v \rangle}^{\alpha_1}))}, g'} = T \end{array} \right)$$

Proof of clause 1

The $VALID(\alpha_2)$ in the VALID clause of Σ and the $\alpha_{1.1}, \alpha_{2.1}, \dots, \alpha_{2.n}$ in the SELECT clause of Σ are not free column references in Σ , because Σ is a binding context for all of them. Σ contains no other column references (and hence no other free column references), apart from those that possibly appear within the $h'_{gparts}(\sigma_g)$ or the Σ' in the FROM clause of Σ . By lemma A.1, this implies (A.257). The definition of $h'_{gparts}(\sigma_g)$ of section 5.9 implies that $FCN(h'_{gparts}(\sigma_g)) = \emptyset$. Hence, (A.257) becomes (A.258).

(A.258) and clause 1' imply (A.259). (A.259) and (A.251) imply (A.260).

$$(A.257) \quad FCN(\Sigma) \subseteq FCN(h'_{gparts}(\sigma_g)) \cup FCN(\Sigma')$$

$$(A.258) \quad FCN(\Sigma) \subseteq FCN(\Sigma')$$

$$(A.259) \quad FCN(\Sigma) \subseteq FCN(\lambda')$$

$$(A.260) \quad FCN(\Sigma) \subseteq \{\alpha_1\} \cup FCN(\lambda)$$

α_1 cannot have a free column reference in Σ . The proof follows. Let us assume that there is a free column reference ζ of α_1 (i.e. of the form $\alpha_1.k$ or $\text{VALID}(\alpha_1)$) in Σ . Then, by the definition of free column reference, (a) ζ is part of Σ . From the translation rule, it is also the case that (b) α_1 is defined by the topmost **FROM** clause of Σ .

If ζ is in the topmost **FROM** clause of Σ , it is either in the $h'_{gparts}(\sigma_g)$ or in the Σ' (the $\text{trans}(\phi', \lambda')$). ζ , however, cannot be in the $h'_{gparts}(\sigma_g)$, because α_1 is generated by the correlation names generator, and it is assumed that the correlation names of the generator do not appear in the **SELECT** statements returned by h'_{gparts} (see section 5.11).

So, if ζ is in the topmost **FROM** clause of Σ , it is in the Σ' , i.e. after the definition of α_1 . Hence, (c) ζ is either not in the topmost **FROM** clause of Σ , or it is in the topmost **FROM** clause of Σ , but it follows the definition of α_1 . (a), (b), and (c) imply that Σ is a binding context for ζ . This implies that ζ is not a free column reference in Σ , which is against the hypothesis. Hence, α_1 cannot have a free column reference in Σ , i.e. $\alpha_1 \notin FCN(\Sigma)$. This and (A.260) imply that $FCN(\Sigma) \subseteq FCN(\lambda)$. Clause 1 has been proven.

Proof of clause 2

According to section 5.9, $FCN(h'_{gparts}(\sigma_g)) = \emptyset$, $\text{eval}(st, h'_{gparts}(\sigma_g)) \in SREL(1)$, and for every $\langle v \rangle \in \text{eval}(st, h'_{gparts}(\sigma_g))$, v represents a period of a gappy partitioning (hence, $v \in D_P$). By clause 2', it is also the case that if $v \in D_P$, then $\text{eval}(st, \Sigma', (g^{db})_{\langle v \rangle}^{\alpha_1}) \in VREL_P(n)$. It should now be easy to see from the translation rule that (A.261) holds.

$$(A.261) \quad \text{eval}(st, \Sigma, g^{db}) = \{ \langle v, v_1, \dots, v_n; v_t \rangle \mid \\ \langle v \rangle \in \text{eval}(st, h'_{gparts}(\sigma_g)), \text{ and } \\ \langle v_1, \dots, v_n; v_t \rangle \in \text{eval}(st, \Sigma', (g^{db})_{\langle v \rangle}^{\alpha_1}) \}$$

$(g^{db})_{\langle v \rangle}^{\alpha_1}$ is used in the last line of (A.261) instead of g^{db} , to capture the fact that if there is any free column reference of α_1 in Σ' , this has to be taken to refer to the $\langle v \rangle$ tuple of $\text{eval}(st, h'_{gparts}(\sigma_g))$ to which α_1 refers.

(A.261) and the discussion above imply that for every $\langle v, v_1, \dots, v_n; v_t \rangle \in \text{eval}(st, \Sigma, g^{db})$, $\langle v_1, \dots, v_n; v_t \rangle \in \text{eval}(st, \Sigma', (g^{db})_{\langle v \rangle}^{\alpha_1}) \in VREL_P(n)$. This implies that $v_t \in D_P$. (A.261) also implies that $\text{eval}(st, \Sigma, g^{db})$ is a valid-time relation of $n + 1$ explicit attributes. Hence, $\text{eval}(st, \Sigma, g^{db}) \in VREL_P(n + 1)$. Clause 2 has been proven.

Proof of clause 3

Using the definition of $\|At[\sigma_g, \beta, \phi']\|^{st, et, lt, g}$ (section 5.5), and the fact that $\|\beta\|^{M(st), g} = g(\beta)$, clause 3 becomes:

$$\begin{aligned}
 (A.262) \quad & \langle v, v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db}) \text{ iff for some } g : \\
 & g \in G \\
 (A.263) \quad & g(\beta) = f_D(v) \\
 (A.264) \quad & \|\tau_1\|^{M(st), g} = f_D(v_1), \dots, \|\tau_n\|^{M(st), g} = f_D(v_n) \\
 (A.265) \quad & g(\beta) \in f_{gparts}(st)(\sigma_g) \\
 (A.266) \quad & \|\phi'\|^{M(st), st, f_D(v_t), f_D(eval(st, \lambda, g^{db})) \cap g(\beta), g} = T
 \end{aligned}$$

I first prove the forward direction of clause 3. I assume that $\langle v, v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$. I need to prove that for some g , (A.262) – (A.266) hold. The assumption that $\langle v, v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$, and (A.261) imply that:

$$\begin{aligned}
 (A.267) \quad & \langle v \rangle \in eval(st, h'_{gparts}(\sigma_g)) \\
 (A.268) \quad & \langle v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma', (g^{db})_{\langle v \rangle}^{\alpha_1})
 \end{aligned}$$

(A.267) and the discussion in the proof of clause 2 imply (A.269).

$$(A.269) \quad v \in D_P$$

(A.269), (A.268), and clause 3' imply that for some g' :

$$\begin{aligned}
 (A.270) \quad & g' \in G \\
 (A.271) \quad & \|\tau_1\|^{M(st), g'} = f_D(v_1), \dots, \|\tau_n\|^{M(st), g'} = f_D(v_n) \\
 (A.272) \quad & \|\phi'\|^{M(st), st, f_D(v_t), f_D(eval(st, \lambda', (g^{db})_{\langle v \rangle}^{\alpha_1})), g'} = T
 \end{aligned}$$

Let $g = (g')_{f_D(v)}^\beta$. Lemma A.7, (A.269), the assumption that $\beta \in VARS$, (A.270), and the definition of g imply (A.262). (A.263) follows from the definition of g .

I now prove (A.266). (A.269), (A.255) (which holds for $v \in D_P$), and (A.263) (already proven) imply (A.273). (A.269), the fact that $D_P \subseteq D$, (A.252) (which holds for $v \in D$), and (A.273) imply (A.274). (A.274) and (A.272) imply (A.275).

$$\begin{aligned}
 (A.273) \quad & f_D(eval(st, \lambda', (g^{db})_{\langle v \rangle}^{\alpha_1})) = g(\beta) \cap f_D(eval(st, \lambda, (g^{db})_{\langle v \rangle}^{\alpha_1})) \\
 (A.274) \quad & f_D(eval(st, \lambda', (g^{db})_{\langle v \rangle}^{\alpha_1})) = g(\beta) \cap f_D(eval(st, \lambda, g^{db})) \\
 (A.275) \quad & \|\phi'\|^{M(st), st, f_D(v_t), f_D(eval(st, \lambda, g^{db})) \cap g(\beta), g'} = T
 \end{aligned}$$

The syntax of TOP (section 5.5) and the fact that $At[\sigma_g, \beta, \phi'] \in YNFORMS$, imply that β does not occur in ϕ' . This and the definition of g imply (A.276). (A.275) and (A.276) imply (A.266).

$$\begin{aligned}
 (A.276) \quad & \|\phi'\|^{M(st), st, f_D(v_t), f_D(eval(st, \lambda, g^{db})) \cap g(\beta), g'} = \\
 & \|\phi'\|^{M(st), st, f_D(v_t), f_D(eval(st, \lambda, g^{db})) \cap g(\beta), (g')_{f_D(v)}^\beta} = \\
 & \|\phi'\|^{M(st), st, f_D(v_t), f_D(eval(st, \lambda, g^{db})) \cap g(\beta), g}
 \end{aligned}$$

(A.264) follows from lemma A.3, the assumption that $\lceil \phi' \rceil = \langle \tau_1, \dots, \tau_n \rangle$, (A.271), and the fact that g and g' assign the same values to all variables, possibly apart from β , which does not occur in ϕ' .

It remains to prove (A.265). The definition of h_{gparts} of section 5.9 and (A.267) imply (A.277). (A.277) and the definition of f_{gparts} of section 5.8 imply (A.278). (A.278) and (A.263) (proven above) imply (A.265). The forward direction of clause 3 has been proven.

$$(A.277) \quad \langle v \rangle \in h_{gparts}(st)(\sigma_g)$$

$$(A.278) \quad f_D(v) \in f_{gparts}(st)(\sigma_g)$$

I now prove the backwards direction of clause 3. I assume that (A.262) – (A.266) hold. I need to prove that $\langle v, v_1, \dots, v_n; v_t \rangle \in eval(st, \Sigma, g^{db})$. According to (A.261), it is enough to prove that (A.267) and (A.268) hold.

(A.263) and (A.265) imply (A.279). (A.279) and the definition of f_{gparts} of section 5.8 imply (A.280). (A.280) and the definition of h_{gparts} of section 5.9 imply (A.267).

$$(A.279) \quad f_D(v) \in f_{gparts}(st)(\sigma_g)$$

$$(A.280) \quad \langle v \rangle \in h_{gparts}(st)(\sigma_g)$$

It remains to prove (A.268). (A.279) implies that $f_D(v) \in PERIODS$, which in turn implies (A.281). (A.281), (A.255) (which holds for $v \in D_P$), (A.252) (which holds for $v \in D$), and (A.263) imply (A.282). (A.266) and (A.282) imply (A.283).

$$(A.281) \quad v \in D_P$$

$$(A.282) \quad f_D(eval(st, \lambda', (g^{db})_{\langle v \rangle}^{\alpha_1})) = g(\beta) \cap f_D(eval(st, \lambda, g^{db}))$$

$$(A.283) \quad \|\phi'\|^{M(st, st, f_D(v_t), f_D(eval(st, \lambda', (g^{db})_{\langle v \rangle}^{\alpha_1})), g)} = T$$

Clause 3', (A.281), (A.262), (A.264), and (A.283) imply (A.268). The backwards direction of clause 3 has been proven.

A.3.16 Before $[\sigma_g, \beta, \phi']$

Translation rule

If $\sigma_g \in GPARTS$, $\beta \in VARS$, $\phi' \in YNFORMS$, and λ is a TSQL2 value expression, then:

$$\begin{aligned} trans(Before[\sigma_g, \beta, \phi'], \lambda) &\stackrel{def}{=} \\ (SELECT DISTINCT \alpha_{1.1}, \alpha_{2.1}, \alpha_{2.2}, \dots, \alpha_{2.n} \\ &\quad VALID VALID(\alpha_2) \\ &\quad FROM (h'_{gparts}(\sigma_g)) AS \alpha_1, trans(\phi', \lambda') AS \alpha_2) \end{aligned}$$

n is the length of $\lceil \phi' \rceil$, λ' is the expression $INTERSECT(PERIOD(TIMESTAMP 'beginning', BEGIN(\alpha_{1.1}) - INTERVAL '1' \chi), \lambda)$, and χ is the TSQL2 name of the granularity of

chronons. Each time the translation rule is used, α_1 and α_2 are two new different correlation names, obtained by calling the correlation names generator after λ has been supplied.

Proof that theorem 5.2 holds for $\phi = \text{Before}[\sigma_g, \beta, \phi']$, if it holds for $\phi = \phi'$

The proof is very similar to that of section A.3.15.

A.3.17 $\text{After}[\sigma_g, \beta, \phi']$

Translation rule

If $\sigma_g \in \text{GPARTS}$, $\beta \in \text{VARS}$, $\phi' \in \text{YNFORMS}$, and λ is a TSQL2 value expression, then:

$$\begin{aligned} \text{trans}(\text{After}[\sigma_g, \beta, \phi'], \lambda) &\stackrel{\text{def}}{=} \\ (\text{SELECT DISTINCT } \alpha_{1.1}, \alpha_{2.1}, \alpha_{2.2}, \dots, \alpha_{2.n} \\ \text{VALID VALID}(\alpha_2) \\ \text{FROM } (h'_{\text{gparts}}(\sigma_g)) \text{ AS } \alpha_1, \text{trans}(\phi', \lambda') \text{ AS } \alpha_2) \end{aligned}$$

n is the length of $\lceil \phi' \rceil$, λ' is the expression $\text{INTERSECT}(\text{PERIOD}(\text{END}(\alpha_{1.1}) + \text{INTERVAL '1' } \chi, \text{TIMESTAMP 'forever'}), \lambda)$, and χ is the TSQL2 name of the granularity of chronons. Each time the translation rule is used, α_1 and α_2 are two new different correlation names, obtained by calling the correlation names generator after λ as been supplied.

Proof that theorem 5.2 holds for $\phi = \text{After}[\sigma_g, \beta, \phi']$, if it holds for $\phi = \phi'$

The proof is very similar to that of section A.3.15.

A.3.18 $\text{At}[\sigma_c, \beta, \phi']$

Translation rule

If $\sigma_c \in \text{CPARTS}$, $\beta \in \text{VARS}$, $\phi' \in \text{YNFORMS}$, and λ is a TSQL2 value expression, then:

$$\begin{aligned} \text{trans}(\text{At}[\sigma_c, \beta, \phi'], \lambda) &\stackrel{\text{def}}{=} \\ (\text{SELECT DISTINCT } \alpha_{1.1}, \alpha_{2.1}, \alpha_{2.2}, \dots, \alpha_{2.n} \\ \text{VALID VALID}(\alpha_2) \\ \text{FROM } (\Sigma_c) \text{ AS } \alpha_1, \text{trans}(\phi', \lambda') \text{ AS } \alpha_2) \end{aligned}$$

n is the length of $\lceil \phi' \rceil$, λ' is the expression $\text{INTERSECT}(\alpha_{1.1}, \lambda)$, and Σ_c is the second element of the pair $\langle \gamma, \Sigma_c \rangle = h'_{\text{cparts}}(\sigma_c)$ (section 5.9). Each time the translation rule is used, α_1 and α_2 are two new different correlation names, obtained by calling the correlation names generator after λ has been supplied.

Proof that theorem 5.2 holds for $\phi = At[\sigma_c, \beta, \phi']$, if it holds for $\phi = \phi'$

The proof is very similar to that of section A.3.15.

A.3.19 *Before* $[\sigma_c, \beta, \phi']$

Translation rule

If $\sigma_c \in CPARTS$, $\beta \in VARS$, $\phi' \in YNFORMS$, and λ is a TSQL2 value expression, then:

$$\begin{aligned} trans(Before[\sigma_c, \beta, \phi'], \lambda) &\stackrel{def}{=} \\ &(\text{SELECT DISTINCT } \alpha_1.1, \alpha_2.1, \alpha_2.2, \dots, \alpha_2.n \\ &\quad \text{VALID VALID}(\alpha_2) \\ &\quad \text{FROM } (\Sigma_c) \text{ AS } \alpha_1, trans(\phi', \lambda') \text{ AS } \alpha_2) \end{aligned}$$

n is the length of $\lceil \phi' \rceil$, λ' is the expression $\text{INTERSECT}(\text{PERIOD}(\text{TIMESTAMP 'beginning'}$, $\text{BEGIN}(\alpha_1.1) - \text{INTERVAL '1' } \chi)$, $\lambda)$, χ is the TSQL2 name of the granularity of chronons, and Σ_c is the second element of the pair $\langle \gamma, \Sigma_c \rangle = h'_{cparts}(\sigma_c)$. Each time the translation rule is used, α_1 and α_2 are two new different correlation names, obtained by calling the correlation names generator after λ has been supplied.

Proof that theorem 5.2 holds for $\phi = Before[\sigma_c, \beta, \phi']$, if it holds for $\phi = \phi'$

The proof is very similar to that of section A.3.15.

A.3.20 *After* $[\sigma_c, \beta, \phi']$

Translation rule

If $\sigma_c \in CPARTS$, $\beta \in VARS$, $\phi' \in YNFORMS$, and λ is a TSQL2 value expression, then:

$$\begin{aligned} trans(After[\sigma_c, \beta, \phi'], \lambda) &\stackrel{def}{=} \\ &(\text{SELECT DISTINCT } \alpha_1.1, \alpha_2.1, \alpha_2.2, \dots, \alpha_2.n \\ &\quad \text{VALID VALID}(\alpha_2) \\ &\quad \text{FROM } (\Sigma_c) \text{ AS } \alpha_1, trans(\phi', \lambda') \text{ AS } \alpha_2) \end{aligned}$$

n is the length of $\lceil \phi' \rceil$, λ' is the expression $\text{INTERSECT}(\text{PERIOD}(\text{END}(\alpha_1.1) + \text{INTERVAL '1' } \chi, \text{TIMESTAMP 'forever'})$, $\lambda)$, χ is the TSQL2 name of the granularity of chronons, and Σ_c is the second element of the pair $\langle \gamma, \Sigma_c \rangle = h'_{cparts}(\sigma_c)$. Each time the translation rule is used, α_1 and α_2 are two new different correlation names, obtained by calling the correlation names generator after λ has been supplied.

Proof that theorem 5.2 holds for $\phi = After[\sigma_c, \beta, \phi']$, if it holds for $\phi = \phi'$

The proof is very similar to that of section A.3.15.

A.3.21 $At[\phi_1, \phi_2]$ **Translation rule**

If $\phi_1, \phi_2 \in YNFORMS$ and λ is a TSQL2 value expression, then:

$$\begin{aligned} trans(At[\phi_1, \phi_2], \lambda) &\stackrel{def}{=} \\ &(\text{SELECT DISTINCT } \alpha_1.1, \alpha_1.2, \dots, \alpha_1.n_1 \alpha_2.1, \alpha_2.2, \dots, \alpha_2.n_2 \\ &\quad \text{VALID VALID}(\alpha_2) \\ &\quad \text{FROM } trans(\phi_1, \lambda_{init})(\text{NOSUBPERIOD}) \text{ AS } \alpha_1, \\ &\quad \quad trans(\phi_2, \lambda') \text{ AS } \alpha_2) \\ &\quad \text{WHERE } \dots \\ &\quad \text{AND } \dots \\ &\quad \vdots \\ &\quad \text{AND } \dots) \end{aligned}$$

λ_{init} is as in section 5.10, λ' is the expression $\text{INTERSECT}(\text{VALID}(\alpha_1), \lambda)$, and n_1, n_2 are the lengths of $\lceil \phi_1 \rceil$ and $\lceil \phi_2 \rceil$ respectively. Each time the translation rule is used, α_1 and α_2 are two new different correlation names, obtained by calling the correlation names generator after λ has been supplied. α_1 is generated after $trans(\phi_1, \lambda_{init})$ has been computed. Assuming that $\lceil \phi_1 \rceil = \langle \tau_1^1, \tau_2^1, \dots, \tau_{n_1}^1 \rangle$ and $\lceil \phi_2 \rceil = \langle \tau_1^2, \dots, \tau_{n_2}^2 \rangle$, the “...”s in the WHERE clause are all the strings in S :

$$\begin{aligned} S = \{ & \text{“}\alpha_1.i = \alpha_2.j\text{”} \mid i \in \{1, 2, 3, \dots, n_1\}, j \in \{1, 2, 3, \dots, n_2\}, \\ & \tau_i^1 = \tau_j^2, \text{ and } \tau_i^1, \tau_j^2 \in VARS \} \end{aligned}$$

Proof that theorem 5.2 holds for $\phi = At[\phi_1, \phi_2]$, if it holds for $\phi = \phi_1$ and $\phi = \phi_2$

I assume that $\phi_1, \phi_2 \in YNFORMS$. By the syntax of TOP, this implies that $At[\phi_1, \phi_2] \in YNFORMS$. I also assume that $st \in PTS$, λ is a TSQL2 value expression, λ' and λ_{init} are as in the translation rule, $g^{db} \in G^{db}$, $eval(st, \lambda, g^{db}) \in D_P^*$, $\lceil \phi_1 \rceil = \langle \tau_1^1, \tau_2^1, \dots, \tau_{n_1}^1 \rangle$, $\lceil \phi_2 \rceil = \langle \tau_1^2, \tau_2^2, \dots, \tau_{n_2}^2 \rangle$, and $\Sigma = trans(At[\phi_1, \phi_2], \lambda)$. From the definition of $\lceil \dots \rceil$, it should be easy to see that:

$$\lceil At[\phi_1, \phi_2] \rceil = \langle \tau_1^1, \tau_2^1, \dots, \tau_{n_1}^1, \tau_1^2, \tau_2^2, \dots, \tau_{n_2}^2 \rangle$$

Finally, I assume that theorem 5.2 holds for $\phi = \phi_1$ and $\phi = \phi_2$. I need to show that:

1. $FCN(\Sigma) \subseteq FCN(\lambda)$
2. $eval(st, \Sigma, g^{db}) \in VREL_P(n_1 + n_2)$
3. $\langle v_1^1, \dots, v_{n_1}^1, v_1^2, \dots, v_{n_2}^2; v_t \rangle \in eval(st, \Sigma, g^{db})$ iff for some $g \in G$:
 $\|\tau_1^1\|^{M(st), g} = f_D(v_1^1), \dots, \|\tau_{n_1}^1\|^{M(st), g} = f_D(v_{n_1}^1),$
 $\|\tau_1^2\|^{M(st), g} = f_D(v_1^2), \dots, \|\tau_{n_2}^2\|^{M(st), g} = f_D(v_{n_2}^2),$ and
 $\|At[\phi_1, \phi_2]\|^{M(st), st, f_D(v_t), f_D(eval(st, \lambda, g^{db})), g} = T$

From the definition of λ' it should be obvious that any free column reference in λ' is either the $\text{VALID}(\alpha_1)$ of λ' , or is situated within the λ of λ' . By lemma A.1, this implies that:

$$(A.284) \quad FCN(\lambda') \subseteq FCN(\text{VALID}(\alpha_1)) \cup FCN(\lambda)$$

The only correlation name that has a free column reference in $\text{VALID}(\alpha_1)$ is α_1 . Hence, $FCN(\text{VALID}(\alpha_1)) = \{\alpha_1\}$, and (A.284) becomes (A.285).

$$(A.285) \quad FCN(\lambda') \subseteq \{\alpha_1\} \cup FCN(\lambda)$$

The α_1 of Σ is generated by calling the correlation names generator after λ has been supplied. Hence, α_1 cannot appear in λ . The fact that α_1 does not appear in λ implies that for every $v_1^1, v_2^1, \dots, v_{n_1}^1 \in D$ and $v_t^1 \in D_T$:

$$(A.286) \quad eval(st, \lambda, (g^{db})_{\langle v_1^1, v_2^1, \dots, v_{n_1}^1; v_t^1 \rangle}^{\alpha_1}) = eval(st, \lambda, g^{db})$$

The fact that for every $v_1^1, v_2^1, \dots, v_{n_1}^1 \in D$ and $v_t^1 \in D_T$, (A.286) holds, and the assumption that $eval(st, \lambda, g^{db}) \in D_P^*$, imply that (A.287) holds for every $v_1^1, \dots, v_{n_1}^1 \in D$ and $v_t^1 \in D_T$.

$$(A.287) \quad f_D(eval(st, \lambda, (g^{db})_{\langle v_1^1, v_2^1, \dots, v_{n_1}^1; v_t^1 \rangle}^{\alpha_1})) \in PERIODS^*$$

By the syntax of TOP, since λ is a value expression, λ' is also a value expression. (A.287) and the definition of λ' imply that (A.288) and (A.289) hold for $v_1^1, \dots, v_{n_1}^1 \in D$ and $v_t^1 \in D_P$ ($D_P \subseteq D_T$).

$$(A.288) \quad f_D(eval(st, \lambda', (g^{db})_{\langle v_1^1, v_2^1, \dots, v_{n_1}^1; v_t^1 \rangle}^{\alpha_1})) = f_D(v_t^1) \cap f_D(eval(st, \lambda, (g^{db})_{\langle v_1^1, v_2^1, \dots, v_{n_1}^1; v_t^1 \rangle}^{\alpha_1}))$$

$$(A.289) \quad eval(st, \lambda', (g^{db})_{\langle v_1^1, v_2^1, \dots, v_{n_1}^1; v_t^1 \rangle}^{\alpha_1}) \in D_P^*$$

By the syntax of TSQL2, λ_{init} is a value expression, and by lemma 5.1, (A.290) – (A.292) hold.

$$(A.290) \quad f_D(eval(st, \lambda_{init}, g^{db})) = PTS$$

$$(A.291) \quad eval(st, \lambda_{init}, g^{db}) \in D_P^*$$

$$(A.292) \quad FCN(\lambda_{init}) = \emptyset$$

Let Σ_1 be the first embedded SELECT statement in the FROM clause of Σ , i.e. $\Sigma_1 = trans(\phi_1, \lambda)$. From the hypothesis and the discussion above, $\phi_1 \in YNFORMS$, $st \in PTS$, $\ulcorner \phi_1 \urcorner = \langle \tau_1^1, \dots, \tau_{n_1}^1 \rangle$, λ_{init} is a TSQL2 value expression, $eval(st, \lambda_{init}, g^{db}) \in D_P^*$, and $g^{db} \in G^{db}$. From theorem 5.2 for $\phi = \phi_1$ (according to the hypothesis, theorem 5.2 holds for $\phi = \phi_1$), and using (A.290) and (A.292), we get:

$$1^1. FCN(\Sigma_1) = \emptyset$$

$$2^1. eval(st, \Sigma_1, g^{db}) \in VREL_P(n_1)$$

- 3¹. $\langle v_1^1, \dots, v_{n_1}^1; v_t^1 \rangle \in eval(st, \Sigma_1, g^{db})$ iff for some $g_1 \in G$:
 $\|\tau_1^1\|^{M(st), g_1} = f_D(v_1^1), \dots, \|\tau_{n_1}^1\|^{M(st), g_1} = f_D(v_{n_1}^1)$, and
 $\|\phi_1\|^{M(st), st, f_D(v_t^1), PTS, g_1} = T$

Let Σ_2 be the second embedded **SELECT** statement in the **FROM** clause of Σ , i.e. $\Sigma_2 = trans(\phi_2, \lambda')$. From the hypothesis, $\phi_2 \in YNFORMS$, $st \in PTS$, $g^{db} \in G^{db}$, and $\lceil \phi_2 \rceil = \langle \tau_1^2, \dots, \tau_{n_2}^2 \rangle$. From the discussion above, λ' is a TSQL2 value expression. If $v_1^1, v_2^1, \dots, v_{n_1}^1 \in D$ and $v_t^1 \in D_P$, then $(g^{db})_{\langle v_1^1, v_2^1, \dots, v_{n_1}^1; v_t^1 \rangle}^{\alpha_1} \in G^{db}$ and (by (A.289)) $eval(st, \lambda', (g^{db})_{\langle v_1^1, v_2^1, \dots, v_{n_1}^1; v_t^1 \rangle}^{\alpha_1}) \in D_P^*$. From theorem 5.2 for $\phi = \phi_2$ (according to the hypothesis, theorem 5.2 holds for $\phi = \phi_2$) we get the following. (The conditions $v_1^1, v_2^1, \dots, v_{n_1}^1 \in D$ and $v_t^1 \in D_P$ do not affect clause 1².)

- 1². $FCN(\Sigma_2) \subseteq FCN(\lambda')$
- 2². If $v_1^1, v_2^1, \dots, v_{n_1}^1 \in D$ and $v_t^1 \in D_P$, then:
 $eval(st, \Sigma_2, (g^{db})_{\langle v_1^1, v_2^1, \dots, v_{n_1}^1; v_t^1 \rangle}^{\alpha_1}) \in VREL_P(n_2)$
- 3². If $v_1^1, v_2^1, \dots, v_{n_1}^1 \in D$ and $v_t^1 \in D_P$, then:
 $(\langle v_1^2, \dots, v_{n_2}^2; v_t^2 \rangle \in eval(st, \Sigma_2, (g^{db})_{\langle v_1^1, v_2^1, \dots, v_{n_1}^1; v_t^1 \rangle}^{\alpha_1}))$ iff for some $g_2 \in G$:
 $\|\tau_1^2\|^{M(st), g_2} = f_D(v_1^2), \dots, \|\tau_{n_2}^2\|^{M(st), g_2} = f_D(v_{n_2}^2)$, and
 $\|\phi_2\|^{M(st), st, f_D(v_t^2), f_D(eval(st, \lambda', (g^{db})_{\langle v_1^1, v_2^1, \dots, v_{n_1}^1; v_t^1 \rangle}^{\alpha_1}))}, g_2} = T$
 $)$

Proof of clause 1

The $VALID(\alpha_2)$ in the **VALID** clause of Σ and the $\alpha_1.1, \dots, \alpha_1.n_1, \alpha_2.1, \dots, \alpha_2.n_2$ in the **SELECT** clause of Σ are not free column references in Σ , because Σ is a binding context for all of them. Any column references of the form $\alpha_1.i$ or $\alpha_2.j$ in the **WHERE** clause of Σ ($i \in \{1, 2, 3, \dots, n_1\}$, $j \in \{1, 2, 3, \dots, n_2\}$; these column references derive from S) are not free column references in Σ for the same reason. Σ contains no other column references (and hence no other free column references), apart from those that possibly appear within the Σ_1 and Σ_2 in the **FROM** clause of Σ . (The reader is reminded that $\Sigma_1 = trans(\phi_1, \lambda_{init})$ and $\Sigma_2 = trans(\phi_2, \lambda')$.) By lemma A.1, this implies (A.293). (A.293), clause 1¹, and clause 1² imply (A.294). (A.294) and (A.285) imply (A.295).

$$(A.293) \quad FCN(\Sigma) \subseteq FCN(\Sigma_1) \cup FCN(\Sigma_2)$$

$$(A.294) \quad FCN(\Sigma) \subseteq FCN(\lambda')$$

$$(A.295) \quad FCN(\Sigma) \subseteq \{\alpha_1\} \cup FCN(\lambda)$$

α_1 cannot have a free column reference in Σ . The proof follows. Let us assume that there is a free column reference ζ of α_1 in Σ (ζ has the form $\alpha_1.k$ or $VALID(\alpha_1)$). Then, by the definition of free column reference, (a) ζ is part of Σ . From the translation rule, it is also the case that (b) α_1 (the correlation name of ζ) is defined by the topmost **FROM** clause of Σ .

If ζ is in the topmost FROM clause of Σ , it can only be in the Σ_1 (the $trans(\phi_1, \lambda_{init})$) or the Σ_2 (the $trans(\phi_2, \lambda')$) of Σ . ζ , however, cannot be in Σ_1 , because α_1 (the correlation name of ζ) is generated after Σ_1 has been computed (see the translation rule), and the correlation names of the generator cannot be used before they have been generated (see section 5.11).

So, if ζ is in the topmost FROM clause of Σ , ζ has to be in the Σ_2 of Σ , i.e. after the definition of α_1 . Hence, (c) ζ is either not in the topmost FROM clause of Σ , or it is in the topmost FROM clause of Σ , but it follows the definition of α_1 . (a), (b), and (c) imply that Σ is a binding context for ζ , which implies that ζ is not a free column reference in Σ . This is against the hypothesis. Hence, α_1 cannot have a free column reference in Σ , i.e. $\alpha_1 \notin FCN(\Sigma)$. This and (A.295) imply that $FCN(\Sigma) \subseteq FCN(\lambda)$. Clause 1 has been proven.

Proof of clause 2

When computing $eval(st, \Sigma, g^{db})$, the α_1 of Σ ranges over the tuples of the relation $nosubperiod(eval(st, \Sigma_1, g^{db}))$. By clause 2¹, $eval(st, \Sigma_1, g^{db}) \in VREL_P(n_1)$. The definition of $nosubperiod$ (section 5.3.2) implies that $nosubperiod(eval(st, \Sigma_1, g^{db}))$ is also a valid-time relation of n_1 explicit attributes, and that all its time-stamps are also time-stamps of $eval(st, \Sigma_1, g^{db})$, i.e. elements of D_P . That is, $eval(st, \Sigma_1, g^{db})$ contains tuples of the form $\langle v_1^1, \dots, v_{n_1}^1; v_t^1 \rangle$, with $v_1^1, \dots, v_{n_1}^1 \in D$ and $v_t^1 \in D_P$. By clause 2², it is also the case that if $v_1^1, \dots, v_{n_1}^1 \in D$ and $v_t^1 \in D_P$, then $eval(st, \Sigma_2, (g^{db})_{\langle v_1^1, \dots, v_{n_1}^1; v_t^1 \rangle}^{\alpha_1}) \in VREL_P(n_2)$. It should now be easy to see from the translation rule that (A.296) holds.

$$\begin{aligned}
 \text{(A.296)} \quad & eval(st, \Sigma, g^{db}) = \\
 & \{ \langle v_1^1, \dots, v_{n_1}^1, v_1^2, \dots, v_{n_2}^2; v_t \rangle \mid \text{for some } v_t^1, \\
 & \langle v_1^1, \dots, v_{n_1}^1; v_t^1 \rangle \in nosubperiod(eval(st, \Sigma_1, g^{db})), \\
 & \langle v_1^2, \dots, v_{n_2}^2; v_t \rangle \in eval(st, \Sigma_2, (g^{db})_{\langle v_1^1, \dots, v_{n_1}^1; v_t^1 \rangle}^{\alpha_1}), \text{ and} \\
 & \text{if } i \in \{1, 2, 3, \dots, n_1\}, j \in \{1, 2, 3, \dots, n_2\}, \tau_i^1, \tau_j^2 \in VARS, \\
 & \text{and } \tau_i^1 = \tau_j^2, \text{ then } v_i^1 = v_j^2 \}
 \end{aligned}$$

$(g^{db})_{\langle v_1^1, \dots, v_{n_1}^1; v_t^1 \rangle}^{\alpha_1}$ is used in the fourth line of (A.297) instead of g^{db} , to capture the fact that if there is any free column reference of α_1 in Σ_2 , this has to be taken to refer to the tuple of $nosubperiod(eval(st, \Sigma_1, g^{db}))$ to which α_1 refers.

Using the definition of *nosubperiod* (section 5.3.2), (A.296) becomes (A.297).

$$\begin{aligned}
 (A.297) \quad & eval(st, \Sigma, g^{db}) = \\
 & \{ \langle v_1^1, \dots, v_{n_1}^1, v_1^2, \dots, v_{n_2}^2; v_t \rangle \mid \text{for some } v_t^1, \\
 & \langle v_1^1, \dots, v_{n_1}^1; v_t^1 \rangle \in eval(st, \Sigma_1, g^{db}), \\
 & \text{there is no } \langle v_1^1, \dots, v_{n_1}^1; v_t^{1'} \rangle \in eval(st, \Sigma_1, g^{db}) \\
 & \text{such that } f_D(v_t^1) \sqsubset f_D(v_t^{1'}), \\
 & \langle v_1^2, \dots, v_{n_2}^2; v_t \rangle \in eval(st, \Sigma_2, (g^{db})_{\langle v_1^1, \dots, v_{n_1}^1; v_t^1 \rangle}^{\alpha_1}), \text{ and} \\
 & \text{if } i \in \{1, 2, 3, \dots, n_1\}, j \in \{1, 2, 3, \dots, n_2\}, \tau_i^1, \tau_j^2 \in VARS, \\
 & \text{and } \tau_i^1 = \tau_j^2, \text{ then } v_i^1 = v_j^2 \}
 \end{aligned}$$

(A.297) and the discussion above imply that for every $\langle v_1^1, \dots, v_{n_1}^1, v_1^2, \dots, v_{n_2}^2; v_t \rangle \in eval(st, \Sigma, g^{db})$, $\langle v_1^2, \dots, v_{n_2}^2; v_t \rangle \in eval(st, \Sigma_2, (g^{db})_{\langle v_1^1, \dots, v_{n_1}^1; v_t^1 \rangle}^{\alpha_1}) \in VREL_P(n_2)$. This implies that $v_t \in D_P$. (A.297) also implies that $eval(st, \Sigma, g^{db})$ is a valid-time relation of $n_1 + n_2$ explicit attributes. Hence, $eval(st, \Sigma, g^{db}) \in VREL_P(n_1 + n_2)$. Clause 2 has been proven.

Proof of clause 3

I now prove clause 3. Using the definition of $\|At[\phi_1, \phi_2]\|^{st, et, lt, g}$ (section 3.10), clause 3 becomes:

$$\begin{aligned}
 & \langle v_1^1, \dots, v_{n_1}^1, v_1^2, \dots, v_{n_2}^2; v_t \rangle \in eval(st, \Sigma, g^{db}) \text{ iff for some } g \text{ and } et' : \\
 (A.298) \quad & g \in G \\
 (A.299) \quad & \|\tau_1^1\|^{M(st), g} = f_D(v_1^1), \dots, \|\tau_{n_1}^1\|^{M(st), g} = f_D(v_{n_1}^1) \\
 (A.300) \quad & \|\tau_1^2\|^{M(st), g} = f_D(v_1^2), \dots, \|\tau_{n_2}^2\|^{M(st), g} = f_D(v_{n_2}^2) \\
 (A.301) \quad & et' \in maxlpers(\{e \in PERIODS \mid \|\phi_1\|^{M(st), st, e, PTS, g} = T\}) \\
 (A.302) \quad & \|\phi_2\|^{M(st), st, f_D(v_t), f_D(eval(st, \lambda, g^{db})) \cap et', g} = T
 \end{aligned}$$

I first prove the forward direction of clause 3. I assume $\langle v_1^1, \dots, v_{n_1}^1, v_1^2, \dots, v_{n_2}^2; v_t \rangle \in eval(st, \Sigma, g^{db})$. I need to prove that for some g and et' , (A.298) – (A.302) hold. The assumption that $\langle v_1^1, \dots, v_{n_1}^1, v_1^2, \dots, v_{n_2}^2; v_t \rangle \in eval(st, \Sigma, g^{db})$ and (A.297) imply that for some v_t^1 :

$$\begin{aligned}
 (A.303) \quad & \langle v_1^1, \dots, v_{n_1}^1; v_t^1 \rangle \in eval(st, \Sigma_1, g^{db}) \\
 (A.304) \quad & \text{there is no } \langle v_1^1, \dots, v_{n_1}^1; v_t^{1'} \rangle \in eval(st, \Sigma_1, g^{db}) \\
 & \text{such that } f_D(v_t^1) \sqsubset f_D(v_t^{1'}), \\
 (A.305) \quad & \langle v_1^2, \dots, v_{n_2}^2; v_t \rangle \in eval(st, \Sigma_2, (g^{db})_{\langle v_1^1, \dots, v_{n_1}^1; v_t^1 \rangle}^{\alpha_1}) \\
 (A.306) \quad & \text{if } i \in \{1, 2, 3, \dots, n_1\}, j \in \{1, 2, 3, \dots, n_2\}, \tau_i^1, \tau_j^2 \in VARS, \\
 & \text{and } \tau_i^1 = \tau_j^2, \text{ then } v_i^1 = v_j^2
 \end{aligned}$$

(A.303) and clause 3¹ imply that for some g_1 :

$$(A.307) \quad g_1 \in G$$

$$(A.308) \quad \|\tau_1^1\|^{M(st),g_1} = f_D(v_1^1), \dots, \|\tau_{n_1}^1\|^{M(st),g_1} = f_D(v_{n_1}^1)$$

$$(A.309) \quad \|\phi_1\|^{M(st),st,f_D(v_t^1),PTS,g_1} = T$$

(A.303) and clause 2¹ imply that:

$$(A.310) \quad v_1^1, \dots, v_{n_1}^1 \in D \text{ and } v_t^1 \in D_P$$

(A.305), (A.310), and clause 3² imply that for some g_2 :

$$(A.311) \quad g_2 \in G$$

$$(A.312) \quad \|\tau_1^2\|^{M(st),g_2} = f_D(v_1^2), \dots, \|\tau_{n_2}^2\|^{M(st),g_2} = f_D(v_{n_2}^2)$$

$$(A.313) \quad \|\phi_2\|^{M(st),st,f_D(v_t),f_D(eval(st,\lambda',(g^{db})_{(v_1^1,v_2^1,\dots,v_{n_1}^1,v_t^1)}^{\alpha_1}))^{g_2}} = T$$

I define the mapping $g : VARS \mapsto OBJS$ as follows:

$$g(\beta) \stackrel{def}{=} \begin{cases} g_1(\beta), & \text{if for some } i \in \{1, 2, 3, \dots, n_1\}, \beta = \tau_i^1 \\ g_2(\beta), & \text{if for some } j \in \{1, 2, 3, \dots, n_2\}, \beta = \tau_j^2 \\ o, & \text{otherwise} \end{cases}$$

where o is a particular element of $OBJS$, chosen arbitrarily. (A.298) follows from lemma A.6, the definition of g , (A.306), (A.308), and (A.312). I set et' as in (A.314), and show that (A.299) – (A.302) hold.

$$(A.314) \quad et' = f_D(v_t^1)$$

The definition of g implies that for every variable β among $\tau_1^1, \dots, \tau_{n_1}^1$, $g(\beta) = g_1(\beta)$. The assumption that $\ulcorner \phi_1 \urcorner = \langle \tau_1^1, \dots, \tau_{n_1}^1 \rangle$ and the definition of $\ulcorner \phi_1 \urcorner$ imply that all the variables of ϕ_1 are among $\tau_1^1, \dots, \tau_{n_1}^1$. Hence, for every variable β in ϕ_1 , $g(\beta) = g_1(\beta)$. Similarly, the definition of g and the assumption that $\ulcorner \phi_2 \urcorner = \langle \tau_1^2, \dots, \tau_{n_2}^2 \rangle$ imply that for every variable β in ϕ_2 , $g(\beta) = g_2(\beta)$.

(A.299) follows from lemma A.3, the assumption that $\langle \tau_1^1, \dots, \tau_{n_1}^1 \rangle = \ulcorner \phi_1 \urcorner$, (A.308), and the fact that g and g_1 assign the same values to all the variables of ϕ_1 . The proof of (A.300) is very similar.

I now prove (A.302). (A.286) and (A.288) (which hold for $v_1^1, \dots, v_{n_1}^1 \in D$ and $v_t^1 \in D_P$) and (A.310) imply (A.315). (A.313), (A.315), (A.314), and the fact that g and g_2 assign the same values to all the variables of ϕ_2 (see above), imply (A.302).

$$(A.315) \quad f_D(eval(st, \lambda', (g^{db})_{(v_1^1,v_2^1,\dots,v_{n_1}^1,v_t^1)}^{\alpha_1})) = f_D(eval(st, \lambda, g^{db})) \cap f_D(v_t^1)$$

It remains to show (A.301). (A.303), clause 2¹, and (A.314) imply (A.316).

$$(A.316) \quad et' \in PERIODS$$

(A.316), (A.314), (A.309), and the fact that g and g_2 assign the same values to all the variables of ϕ_1 imply (A.317).

$$(A.317) \quad et' \in \{e \in PERIODS \mid \|\phi_1\|^{M(st),st,e,PTS,g} = T\}$$

To prove (A.301) it remains to prove that there is no et'' that satisfies both (A.318) and (A.319).

$$(A.318) \quad et'' \in \{e \in PERIODS \mid \|\phi_1\|^{M(st),st,e,PTS,g} = T\}$$

$$(A.319) \quad et' \sqsubset et''$$

Let us assume that for some et'' , (A.318) and (A.319) hold. (A.318) and the fact that g and g_1 assign the same values to the variables of ϕ_1 imply that:

$$(A.320) \quad \|\phi'\|^{M(st),st,et'',PTS,g_1} = T$$

$$(A.321) \quad et'' \in PERIODS$$

I set $v_t^{1'} = f_D^{-1}(et'')$, which implies (A.322). (A.307), (A.308), (A.322), (A.320), and clause 3¹ imply (A.323). (A.319), (A.314), and (A.322) imply (A.324).

$$(A.322) \quad et'' = f_D(v_t^{1'})$$

$$(A.323) \quad \langle v_1, \dots, v_n; v_t^{1'} \rangle \in eval(st, \Sigma_1, g^{db})$$

$$(A.324) \quad f_D(v_t^1) \sqsubset f_D(v_t^{1'})$$

(A.323) and (A.324) are against (A.304). Therefore, there can be no et'' that satisfies (A.318) and (A.319). (A.301) and the forward direction of clause 3 have been proven.

I now prove the backwards direction of clause 3. I assume that for some g and et' , (A.298) – (A.302) hold. I must show that $\langle v_1^1, \dots, v_{n_1}^1, v_1^2, \dots, v_{n_2}^2; v_t \rangle \in eval(st, \Sigma, g^{db})$. According to (A.297), it is enough to prove that for some v_t^1 , (A.303) – (A.306) hold.

I first prove (A.303). I set $v_t^1 = f_D^{-1}(et')$, which implies (A.325). (A.301) implies (A.326). Clause 3¹, (A.298), (A.299), (A.325), and (A.326) imply (A.303).

$$(A.325) \quad et' = f_D(v_t^1)$$

$$(A.326) \quad \|\phi_1\|^{M(st),st,et',PTS,g} = T$$

I now prove (A.305). (A.303) (proven above) and clause 2¹ (also proven above) imply that:

$$(A.327) \quad v_1^1, \dots, v_{n_1}^1 \in D \text{ and } v_t^1 \in D_P$$

(A.286) and (A.288) (which hold for $v_1^1, \dots, v_{n_1}^1 \in D$ and $v_t^1 \in D_P$), (A.327), and (A.325) imply (A.328). Clause 3², (A.327), (A.298), (A.300), (A.328), and (A.302) imply (A.305).

$$(A.328) \quad f_D(eval(st, \lambda', (g^{db})_{\langle v_1^1, v_2^1, \dots, v_{n_1}^1; v_t^1 \rangle}^{\alpha_1})) = f_D(eval(st, \lambda, g^{db})) \cap et'$$

I now prove (A.306). Let us assume that $i \in \{1, 2, 3, \dots, n_1\}$, $j \in \{1, 2, 3, \dots, n_2\}$, $\tau_i^1, \tau_j^2 \in VARS$, and $\tau_i^1 = \tau_j^2$. From (A.299) we get (A.329), and from (A.300) we get (A.330).

$$(A.329) \quad \|\tau_j^1\|^{M(st),g} = f_D(v_i^1)$$

$$(A.330) \quad \|\tau_j^2\|^{M(st),g} = f_D(v_j^2)$$

(A.329), (A.330), and the hypothesis that $\tau_i^1 = \tau_j^2$ imply that $f_D(v_i^1) = f_D(v_j^2)$. This in turn implies that $f_D^{-1}(f_D(v_i^1)) = f_D^{-1}(f_D(v_j^2))$, i.e. that $v_i^1 = v_j^2$. (A.306) has been proven.

It remains to prove (A.304). Let us assume that there is a tuple $\langle v_1^1, \dots, v_n^1; v_t^{1'} \rangle$, such that (A.331) and (A.332) hold.

$$(A.331) \quad \langle v_1^1, \dots, v_n^1; v_t^{1'} \rangle \in eval(st, \Sigma_1, g^{db})$$

$$(A.332) \quad f_D(v_t^1) \sqsubset f_D(v_t^{1'})$$

(A.331) and clause 3¹ imply that for some g' :

$$(A.333) \quad g' \in G$$

$$(A.334) \quad \|\tau_1\|^{M(st), g'} = f_D(v_1^1), \dots, \|\tau_n\|^{M(st), g'} = f_D(v_n^1)$$

$$(A.335) \quad \|\phi_1\|^{M(st), st, f_D(v_t^{1'}), PTS, g'} = T$$

Lemma A.4, (A.298), (A.333), the assumptions that $\phi_1 \in YNFORMS$ and $\lceil \phi_1 \rceil = \langle \tau_1^1, \dots, \tau_{n_1}^1 \rangle$, (A.299), and (A.334) imply that g and g' assign the same values to the variables of ϕ_1 . This implies (A.336). (A.335) and (A.336) imply (A.337).

$$(A.336) \quad \|\phi_1\|^{M(st), st, f_D(v_t^{1'}), PTS, g'} = \|\phi_1\|^{M(st), st, f_D(v_t^{1'}), PTS, g}$$

$$(A.337) \quad \|\phi_1\|^{M(st), st, f_D(v_t^{1'}), PTS, g} = T$$

I set et'' as in (A.338). (A.332), (A.325), and (A.338) imply (A.339). (A.337) and (A.338) imply (A.340).

$$(A.338) \quad et'' = f_D(v_t^{1'})$$

$$(A.339) \quad et' \sqsubset et''$$

$$(A.340) \quad \|\phi_1\|^{M(st), st, et'', PTS, g} = T$$

(A.339) and (A.340) are against (A.301), because (A.301) and the definition of *mxlpers* (section 3.3) imply that there is no et'' , such that $et' \sqsubset et''$ and $\|\phi_1\|^{M(st), st, et'', PTS, g} = T$. Therefore, there can be no tuple $\langle v_1^1, \dots, v_n^1; v_t^{1'} \rangle$ such that (A.331) and (A.332) hold. (A.304) and the backwards direction of clause 3 have been proven.

A.3.22 Before $[\phi_1, \phi_2]$

Translation rule

If $\phi_1, \phi_2 \in YNFORMS$ and λ is a TSQL2 value expression, then:

```

trans(Before $[\phi_1, \phi_2]$ ,  $\lambda$ )  $\stackrel{def}{=}$ 
(SELECT DISTINCT  $\alpha_1.1, \alpha_1.2, \dots, \alpha_1.n_1 \alpha_2.1, \alpha_2.2, \dots, \alpha_2.n_2$ 
  VALID VALID( $\alpha_2$ )
FROM trans( $\phi_1, \lambda_{init}$ )(NOSUBPERIOD) AS  $\alpha_1$ ,
  trans( $\phi_2, \lambda'$ ) AS  $\alpha_2$ )
WHERE ...
AND ...
:
AND ... )

```


λ_{init} is as in section 5.10, λ' is the expression `INTERSECT(PERIOD(TIMESTAMP 'beginning', BEGIN(VALID(α_1)) - INTERVAL '1' χ), λ)`, and χ is the TSQL2 name of the granularity of chronons. n_1 and n_2 are the lengths of $\lceil \phi_1 \rceil$ and $\lceil \phi_2 \rceil$ respectively. Each time the translation rule is used, α_1 and α_2 are two new different correlation names, obtained by calling the correlation names generator after λ has been supplied. α_1 is generated after $trans(\phi_1, \lambda_{init})$ has been computed, and before computing $trans(\phi_2, \lambda')$. Assuming that $\lceil \phi_1 \rceil = \langle \tau_1^1, \dots, \tau_{n_1}^1 \rangle$ and $\lceil \phi_2 \rceil = \langle \tau_1^2, \dots, \tau_{n_2}^2 \rangle$, the “...”s in the WHERE clause are all the strings in the set S of section A.3.21.

Proof that theorem 5.2 holds for $\phi = Before[\phi_1, \phi_2]$, if it holds for $\phi = \phi_1$ and $\phi = \phi_2$

The proof is very similar to that of section A.3.21.

A.3.23 *After* $[\phi_1, \phi_2]$

Translation rule

If $\phi_1, \phi_2 \in YNFORMS$ and λ is a TSQL2 value expression, then:

$$trans(After[\phi_1, \phi_2], \lambda) \stackrel{def}{=} \\ \begin{aligned} & (SELECT DISTINCT \alpha_1.1, \alpha_1.2, \dots, \alpha_1.n_1 \alpha_2.1, \alpha_2.2, \dots, \alpha_2.n_2 \\ & \quad VALID VALID(\alpha_2) \\ & \quad FROM trans(\phi_1, \lambda_{init})(NOSUBPERIOD) AS \alpha_1, \\ & \quad \quad trans(\phi_2, \lambda') AS \alpha_2) \\ & \quad WHERE \dots \\ & \quad \quad AND \dots \\ & \quad \quad \vdots \\ & \quad \quad AND \dots) \end{aligned}$$

n_1, n_2 are the lengths of $\lceil \phi_1 \rceil$ and $\lceil \phi_2 \rceil$ respectively. λ_{init} is as in section 5.10, λ' is the expression `INTERSECT(PERIOD(END(VALID(α_1)) + INTERVAL '1' χ , TIMESTAMP 'forever'), λ)`, and χ is the TSQL2 name of the granularity of chronons. Each time the translation rule is used, α_1 and α_2 are two new different correlation names, obtained by calling the correlation names generator after λ has been supplied. α_1 is generated after $trans(\phi_1, \lambda_{init})$ has been computed, and before computing $trans(\phi_2, \lambda')$. Assuming that $\lceil \phi_1 \rceil = \langle \tau_1^1, \dots, \tau_{n_1}^1 \rangle$ and $\lceil \phi_2 \rceil = \langle \tau_1^2, \dots, \tau_{n_2}^2 \rangle$, the “...”s in the WHERE clause are all the strings in the set S of section A.3.21.

Proof that theorem 5.2 holds for $\phi = After[\phi_1, \phi_2]$, if it holds for $\phi = \phi_1$ and $\phi = \phi_2$

The proof is very similar to that of section A.3.21.

A.4 Translation rules for wh-formulae and proof of theorem 5.1

This section lists the translation rules for wh-formulae. These rules have to satisfy theorem 5.1 (see section 5.10). There are two translation rules for wh-formulae. They correspond to the cases where the TOP formula ϕ to be translated belongs to $WHFORMS_1$ or $WHFORMS_2$ (see section 3.2). Each rule is followed by a proof that theorem 5.1 holds if $\phi \in WHFORMS_1$ or $\phi \in WHFORMS_2$ respectively.

As explained in section 5.11, the translation rules for wh-formulae define $trans(\phi, \lambda)$ only for $\lambda = \lambda_{init}$. The values of $trans(\phi, \lambda)$ for $\phi \in WHFORMS$ and $\lambda \neq \lambda_{init}$ are not used anywhere (they are also not examined by theorem 5.1) and can be chosen arbitrarily.

A.4.1 $? \beta_1 ? \beta_2 ? \beta_3 \dots ? \beta_n \phi'$

Translation rule

If $\beta_1, \beta_2, \dots, \beta_n \in VARS$, $\phi' \in YNFORMS$, and λ_{init} is as in section 5.10, then:

$$trans(? \beta_1 ? \beta_2 ? \beta_3 \dots ? \beta_n \phi', \lambda_{init}) \stackrel{def}{=} \\ (\text{SELECT DISTINCT SNAPSHOT } \alpha.\omega_1, \alpha.\omega_2, \alpha.\omega_3, \dots, \alpha.\omega_n \\ \text{FROM } trans(\phi', \lambda_{init}) \text{ AS } \alpha)$$

Each time the translation rule is used, α is a new correlation name, obtained by calling the correlation names generator. For every $i \in \{1, 2, 3, \dots, n\}$,

$$\omega_i = \min(\{j \mid j \in \{1, 2, 3, \dots, k\} \text{ and } \tau_j = \beta_i\})$$

where $\langle \tau_1, \tau_2, \tau_3, \dots, \tau_k \rangle = \lceil \phi' \rceil$. That is, the first position (from left to right) where β_i appears in $\langle \tau_1, \dots, \tau_k \rangle$ is the ω_i -th one.

Proof that theorem 5.1 holds for $\phi = ? \beta_1 ? \beta_2 ? \beta_3 \dots ? \beta_n \phi'$

I assume that $\beta_1, \beta_2, \dots, \beta_n \in VARS$ and $\phi' \in YNFORMS$. By the syntax of TOP, this implies that $? \beta_1 ? \beta_2 ? \beta_3 \dots ? \beta_n \phi' \in WHFORMS$. I also assume that $st \in PTS$, λ_{init} is as in section 5.10, $\Sigma = trans(? \beta_1 ? \beta_2 ? \beta_3 \dots ? \beta_n \phi', \lambda_{init})$, and that $\lceil \phi' \rceil = \langle \tau_1, \dots, \tau_k \rangle$ (as in the translation rule). I need to show that:

1. $FCN(\Sigma) = \emptyset$
2. $eval(st, \Sigma) \in SREL(n)$
3. $\{\langle f_D(v_1), \dots, f_D(v_n) \rangle \mid \langle v_1, \dots, v_n \rangle \in eval(st, \Sigma)\} = \\ \parallel ? \beta_1 ? \beta_2 ? \beta_3 \dots ? \beta_n \phi' \parallel^{M(st), st}$

According to the syntax of TSQL2, λ_{init} is a value expression. Let g^{db} be an arbitrary member of G^{db} . By lemma 5.1, (A.341) – (A.343) hold.

$$(A.341) \quad f_D(eval(st, \lambda_{init}, g^{db})) = PTS$$

$$(A.342) \quad eval(st, \lambda_{init}, g^{db}) \in D_P^*$$

$$(A.343) \quad FCN(\lambda_{init}) = \emptyset$$

Let Σ' be the **SELECT** statement in the **FROM** clause of Σ , i.e. $\Sigma' = trans(\phi', \lambda_{init})$. From the hypothesis and the discussion above, $\phi' \in YNFORMS$, $st \in PTS$, $\lceil \phi' \rceil = \langle \tau_1, \dots, \tau_k \rangle$, $g^{db} \in G^{db}$, λ_{init} is a TSQL2 value expression, and $eval(st, \lambda_{init}, g^{db}) \in D_P^*$. Then, from theorem 5.2 (already proven), and using (A.341) and (A.343), we get:

$$1'. FCN(\Sigma') = \emptyset$$

$$2'. eval(st, \Sigma') \in VREL_P(k)$$

$$3'. \langle v'_1, \dots, v'_k; v'_t \rangle \in eval(st, \Sigma') \text{ iff for some } g \in G: \\ \|\tau_1\|^{M(st),g} = f_D(v'_1), \dots, \|\tau_k\|^{M(st),g} = f_D(v'_k), \text{ and } \|\phi'\|^{M(st),st,f_D(v'_t),PTS,g} = T$$

In clauses 2' and 3' I have not included g^{db} among the arguments of $eval(st, \Sigma')$, because according to clause 1', $FCN(\Sigma') = \emptyset$ (see comments in section 5.4).

Proof of clause 1

The $\alpha.\omega_1, \dots, \alpha.\omega_n$ in the **SELECT** clause of Σ are not free column references in Σ , because Σ is a binding context for all of them. Σ contains no other column references (and hence no other free column references), apart from those that possibly appear within Σ' . By lemma A.1, this implies (A.344). Clause 1' and (A.344) imply clause 1.

$$(A.344) \quad FCN(\Sigma) \subseteq FCN(\Sigma')$$

Proof of clause 2

When computing $eval(st, \Sigma)$, the α of Σ ranges over the tuples of $eval(st, \Sigma')$. (I do not include in the arguments of $eval(st, \Sigma)$ and $eval(st, \Sigma')$ the assignment to the correlation names, because according to clauses 1 and 1', $FCN(\Sigma) = FCN(\Sigma') = \emptyset$.) By clause 2', $eval(st, \Sigma') \in VREL_P(k)$. Hence, α ranges over tuples of the form $\langle v'_1, \dots, v'_k; v'_t \rangle \in eval(st, \Sigma')$.

The syntax of TOP (section 3.2) and the fact that $? \beta_1 \dots ? \beta_n \phi' \in WHFORMS$ imply that for every $i \in \{1, 2, 3, \dots, n\}$, β_i occurs at least once within ϕ' . This and the definition of $\lceil \dots \rceil$ imply that β_i occurs at least once within $\lceil \phi' \rceil$, which according to the hypothesis is $\langle \tau_1, \dots, \tau_k \rangle$. Hence, for every $i \in \{1, 2, 3, \dots, n\}$, the set $\{j \mid j \in \{1, 2, 3, \dots, k\} \text{ and } \tau_j = \beta_i\}$ in the definition of ω_i (see the translation rule) is not empty, and $\omega_i \in \{1, 2, 3, \dots, k\}$. Assuming that α refers to a tuple $\langle v'_1, \dots, v'_k; v'_t \rangle \in eval(st, \Sigma')$, for every $i \in \{1, 2, 3, \dots, n\}$, the $\alpha.\omega_i$ of Σ (see the translation rule) refers to v'_{ω_i} , i.e. the ω_i -th (from left to right) among v'_1, v'_2, \dots, v'_k .

It should now be easy to see from the translation rule that:

$$(A.345) \quad eval(st, \Sigma) = \{ \langle v'_{\omega_1}, v'_{\omega_2}, v'_{\omega_3}, \dots, v'_{\omega_n} \rangle \mid \\ \langle v'_1, v'_2, v'_3, \dots, v'_k; v'_t \rangle \in eval(st, \Sigma'), \text{ and} \\ \text{for every } i \in \{1, 2, 3, \dots, n\}, \\ \omega_i = \min(\{j \mid j \in \{1, 2, 3, \dots, k\} \text{ and } \tau_j = \beta_i\}) \}$$

(A.345) implies that $eval(st, \Sigma)$ is a snapshot relation of n attributes. Clause 2 has been proven.

Proof of clause 3

By the definitions of $\|\phi\|^{M(st), st}$ and $\|\phi\|^{M(st), st, et, lt, g}$ for $\phi \in WHFORMS_1$ (section 3.6), clause 3 becomes:

$$(A.346) \quad \{ \langle f_D(v_1), f_D(v_2), \dots, f_D(v_n) \rangle \mid \langle v_1, v_2, \dots, v_n \rangle \in eval(st, \Sigma) \} \\ = \bigcup_{g \in G, et \in PERIODS} \{ \langle g(\beta_1), g(\beta_2), \dots, g(\beta_n) \rangle \mid \|\phi'\|^{M(st), st, et, PTS, g} = T \}$$

I prove (A.346) by proving that its left-hand side (LHS) is a subset of its right-hand side (RHS), and that its RHS is a subset of its LHS. I start with the proof that the LHS of (A.346) is a subset of the RHS. I assume that for some $v_1, \dots, v_n \in D$, $\langle f_D(v_1), \dots, f_D(v_n) \rangle$ is an element of the LHS of (A.346), i.e. that (A.347) holds.

$$(A.347) \quad \langle v_1, \dots, v_n \rangle \in eval(st, \Sigma)$$

I need to prove that $\langle f_D(v_1), \dots, f_D(v_n) \rangle$ is an element of the RHS of (A.346), i.e. that for some g and et :

$$(A.348) \quad g \in G$$

$$(A.349) \quad et \in PERIODS$$

$$(A.350) \quad f_D(v_1) = g(\beta_1), \dots, f_D(v_n) = g(\beta_n)$$

$$(A.351) \quad \|\phi'\|^{M(st), st, et, PTS, g} = T$$

(A.347) and (A.345) imply that for some v'_1, \dots, v'_k, v'_t :

$$(A.352) \quad \langle v'_1, \dots, v'_k; v'_t \rangle \in eval(st, \Sigma')$$

$$(A.353) \quad v_1 = v'_{\omega_1}, v_2 = v'_{\omega_2}, \dots, v_n = v'_{\omega_n}$$

$$(A.354) \quad \text{for every } i \in \{1, 2, 3, \dots, n\}, \\ \omega_i = \min(\{j \mid j \in \{1, 2, 3, \dots, k\} \text{ and } \tau_j = \beta_i\})$$

(A.352) and clause 3' imply that for some g :

$$(A.355) \quad g \in G$$

$$(A.356) \quad \|\tau_1\|^{M(st), g} = f_D(v'_1), \dots, \|\tau_k\|^{M(st), g} = f_D(v'_k)$$

$$(A.357) \quad \|\phi'\|^{M(st), st, f_D(v'_t), PTS, g} = T$$

(A.348) is the same as (A.355), which is known to be true. I set et as in (A.358). Then, (A.351) follows from (A.357). (A.352) and clause 2' imply (A.359). (A.349) follows from (A.358) and (A.359).

$$(A.358) \quad et = f_D(v'_t)$$

$$(A.359) \quad v'_t \in D_P$$

It remains to prove (A.350). For every $i \in \{1, 2, 3, \dots, n\}$, since $\beta_i \in VARS$, according to the semantics of TOP, (A.360) holds. (A.354) implies (A.361) and (A.362).

$$(A.360) \quad g(\beta_i) = \|\beta_i\|^{M(st),g}$$

$$(A.361) \quad \tau_{\omega_i} = \beta_i$$

$$(A.362) \quad \omega_i \in \{1, 2, 3, \dots, k\}$$

(A.361) and (A.360) imply (A.363). (A.362) and (A.356) imply (A.364). (A.363) and (A.364) imply (A.365).

$$(A.363) \quad g(\beta_i) = \|\tau_{\omega_i}\|^{M(st),g}$$

$$(A.364) \quad \|\tau_{\omega_i}\|^{M(st),g} = f_D(v'_{\omega_i})$$

$$(A.365) \quad g(\beta_i) = f_D(v'_{\omega_i})$$

(A.353) and the assumption that $i \in \{1, 2, 3, \dots, n\}$, imply (A.366). (A.366) and (A.365) imply (A.367).

$$(A.366) \quad v'_{\omega_i} = v_i$$

$$(A.367) \quad g(\beta_i) = f_D(v_i)$$

I have proven that for every $i \in \{1, 2, 3, \dots, n\}$, $f_D(v_i) = g(\beta_i)$. Therefore, (A.350) holds. The proof that the LHS of (A.346) is a subset of the RHS has been completed.

I now prove that the RHS of (A.346) is a subset of the LHS. I assume that for some $g \in G$, $\langle g(\beta_1), g(\beta_2), \dots, g(\beta_n) \rangle$ is an element of the RHS of (A.346), i.e. that for some g and et , (A.368) – (A.370) hold.

$$(A.368) \quad g \in G$$

$$(A.369) \quad et \in PERIODS$$

$$(A.370) \quad \|\phi'\|^{M(st),st,et,PTS,g} = T$$

I need to prove that $\langle g(\beta_1), g(\beta_2), \dots, g(\beta_n) \rangle$ is an element of the LHS of (A.346), i.e. that for some $v_1, \dots, v_n \in D$:

$$(A.371) \quad g(\beta_1) = f_D(v_1), \dots, g(\beta_n) = f_D(v_n)$$

$$(A.372) \quad \langle v_1, \dots, v_n \rangle \in eval(st, \Sigma)$$

I set v_1, \dots, v_n as in (A.373), which implies that $v_1, \dots, v_n \in D$ and that (A.371) holds.

$$(A.373) \quad v_1 = f_D^{-1}(g(\beta_1)), \dots, v_n = f_D^{-1}(g(\beta_n))$$

It remains to prove (A.372). By (A.345), it is enough to prove that for some $v'_1, v'_2, \dots, v'_k, v'_t, \omega_1, \omega_2, \dots, \omega_n$:

$$(A.374) \quad \langle v'_1, \dots, v'_k; v'_t \rangle \in eval(st, \Sigma')$$

$$(A.375) \quad v_1 = v'_{\omega_1}, \dots, v_n = v'_{\omega_n}$$

$$(A.376) \quad \text{for every } i \in \{1, 2, 3, \dots, n\}, \\ \omega_i = \min(\{j \mid j \in \{1, 2, 3, \dots, k\} \text{ and } \tau_j = \beta_i\})$$

I set v'_1, v'_2, \dots, v'_k as in (A.377), which implies (A.378). I also set $v'_t = f_D^{-1}(et)$, which implies (A.379). Clause 3', (A.368), (A.378), (A.379), and (A.370) imply (A.374).

$$(A.377) \quad v'_1 = f_D^{-1}(\|\tau_1\|^{M(st),g}), \dots, v'_k = f_D^{-1}(\|\tau_k\|^{M(st),g})$$

$$(A.378) \quad \|\tau_1\|^{M(st),g} = f_D(v'_1), \dots, \|\tau_k\|^{M(st),g} = f_D(v'_k)$$

$$(A.379) \quad et = f_D(v'_t)$$

For every $i \in \{1, 2, 3, \dots, n\}$, I set ω_i as in (A.376). It remains to prove (A.375). (A.373) implies that for every $i \in \{1, 2, 3, \dots, n\}$, (A.380) holds. Since $\beta_i \in VARS$, from the semantics of TOP we get (A.381). (A.380) and (A.381) imply (A.382).

$$(A.380) \quad v_i = f_D^{-1}(g(\beta_i))$$

$$(A.381) \quad g(\beta_i) = \|\beta_i\|^{M(st),g}$$

$$(A.382) \quad v_i = f_D^{-1}(\|\beta_i\|^{M(st),g})$$

(A.376) (which holds; see above) and the assumption that $i \in \{1, 2, 3, \dots, n\}$ imply that:

$$(A.383) \quad \beta_i = \tau_{\omega_i}$$

$$(A.384) \quad \omega_i \in \{1, 2, 3, \dots, k\}$$

Using (A.383), (A.382) becomes (A.385). (A.384) and (A.377) imply (A.386).

$$(A.385) \quad v_i = f_D^{-1}(\|\tau_{\omega_i}\|^{M(st),g})$$

$$(A.386) \quad v'_{\omega_i} = f_D^{-1}(\|\tau_{\omega_i}\|^{M(st),g})$$

(A.385) and (A.386) imply that $v_i = v'_{\omega_i}$. I have proven that for every $i \in \{1, 2, 3, \dots, n\}$, $v_i = v'_{\omega_i}$. Hence, (A.375) holds. The proof that the RHS of (A.346) is a subset of the LHS has been completed.

A.4.2 $?_{maxl}\beta_1 ?\beta_2 ?\beta_3 \dots ?\beta_n \phi'$

Translation rule

If $\beta_1, \beta_2, \dots, \beta_n \in VARS$, $\phi' \in YNFORMS$, and λ_{init} is as in section 5.10, then:

$$\begin{aligned} trans(?_{maxl}\beta_1 ?\beta_2 ?\beta_3 \dots ?\beta_n \phi', \lambda_{init}) &\stackrel{def}{=} \\ (SELECT DISTINCT SNAPSHOT VALID(\alpha_2), \alpha_2.2, \alpha_2.3, \dots, \alpha_2.n \\ FROM (SELECT DISTINCT 'dummy', \alpha_1.\omega_2, \alpha_1.\omega_3, \dots, \alpha_1.\omega_n \\ VALID \alpha_1.\omega_1 \\ FROM trans(\phi', \lambda_{init}) AS \alpha_1 \\) (NOSUBPERIOD) AS \alpha_2) \end{aligned}$$

Each time the translation rule is used, α_1 and α_2 are two different new correlation names, obtained by calling the correlation names generator. For every $i \in \{1, 2, 3, \dots, n\}$,

$$\omega_i = \min(\{j \mid j \in \{1, 2, 3, \dots, k\} \text{ and } \tau_j = \beta_i\})$$

where $\langle \tau_1, \tau_2, \tau_3, \dots, \tau_k \rangle = \lceil \phi' \rceil$. That is, the first position (from left to right) where β_i appears in $\langle \tau_1, \dots, \tau_k \rangle$ is the ω_i -th one.

Proof that theorem 5.1 holds for $\phi = ?_{mxl}\beta_1 ?\beta_2 ?\beta_3 \dots ?\beta_n \phi'$

I assume that $\beta_1, \beta_2, \dots, \beta_n \in \text{VARS}$ and $\phi' \in \text{YNFORMS}$. By the syntax of TOP, this implies that $?_{mxl}\beta_1 ?\beta_2 ?\beta_3 \dots ?\beta_n \phi' \in \text{WHFORMS}$. I also assume that $st \in \text{PTS}$, λ_{init} is as in section 5.10, $\Sigma = \text{trans}(_{mxl}\beta_1 ?\beta_2 ?\beta_3 \dots ?\beta_n \phi', \lambda_{init})$, and that $\lceil \phi' \rceil = \langle \tau_1, \dots, \tau_k \rangle$ (as in the translation rule). I need to show that:

1. $\text{FCN}(\Sigma) = \emptyset$
2. $\text{eval}(st, \Sigma) \in \text{SREL}(n)$
3. $\{\langle f_D(v_1), \dots, f_D(v_n) \rangle \mid \langle v_1, \dots, v_n \rangle \in \text{eval}(st, \Sigma)\} = \|\text{?}_{mxl}\beta_1 ?\beta_2 ?\beta_3 \dots ?\beta_n \phi'\|^{M(st), st}$

Let Σ' be the embedded SELECT statement to which α_1 refers, i.e. $\Sigma' = \text{trans}(\phi', \lambda_{init})$. Following exactly the same steps as in section A.4.1, we arrive at the conclusion that:

- 1'. $\text{FCN}(\Sigma') = \emptyset$
- 2'. $\text{eval}(st, \Sigma') \in \text{VREL}_P(k)$
- 3'. $\langle v'_1, \dots, v'_k; v'_t \rangle \in \text{eval}(st, \Sigma')$ iff for some $g \in G$:
 $\|\tau_1\|^{M(st), g} = f_D(v'_1), \dots, \|\tau_k\|^{M(st), g} = f_D(v'_k)$, and $\|\phi'\|^{M(st), st, f_D(v'_t), PTS, g} = T$

Proof of clause 1

The $\text{VALID}(\alpha_2), \alpha_2.2, \dots, \alpha_2.n$ in the SELECT clause of Σ are not free column references in Σ , because Σ is a binding context for all of them. The $\alpha_1.\omega_1, \dots, \alpha_1.\omega_n$ in the VALID and the SELECT clauses of the embedded SELECT statement to which α_2 refers are also not free column references in Σ , because the SELECT statement to which α_2 refers is a binding context for all of them. Σ contains no other column references (and hence no other free column references), apart from those that possibly appear within Σ' (the $\text{trans}(\phi', \lambda_{init})$). By lemma A.1, this implies (A.387). Clause 1' and (A.387) imply clause 1.

$$(A.387) \quad \text{FCN}(\Sigma) \subseteq \text{FCN}(\Sigma')$$

Proof of clause 2

When computing $eval(st, \Sigma)$, the α_1 of Σ ranges over the tuples of $eval(st, \Sigma')$. (I do not include in the arguments of $eval(st, \Sigma)$ and $eval(st, \Sigma')$ the assignment to the correlation names, because according to clauses 1 and 1', $FCN(\Sigma) = FCN(\Sigma') = \emptyset$.) By clause 2', $eval(st, \Sigma') \in VREL_P(k)$. Hence, α_1 ranges over tuples of the form $\langle v'_1, \dots, v'_k; v'_t \rangle \in eval(st, \Sigma')$.

The syntax of TOP (section 3.2) and the fact that $?_{maxl}\beta_1 \dots ?_{\beta_n} \phi' \in WHFORMS$ imply that for every $i \in \{1, 2, 3, \dots, n\}$, β_i occurs at least once within ϕ' . This and the definition of $\lceil \dots \rceil$ imply that β_i occurs at least once within $\lceil \phi' \rceil$, which according to the hypothesis is $\langle \tau_1, \dots, \tau_k \rangle$. Hence, for every $i \in \{1, 2, 3, \dots, n\}$, the set $\{j \mid j \in \{1, 2, 3, \dots, k\} \text{ and } \tau_j = \beta_i\}$ in the definition of ω_i (see the translation rule) is not empty, and $\omega_i \in \{1, 2, 3, \dots, k\}$. Assuming that α_1 refers to a tuple $\langle v'_1, \dots, v'_k; v'_t \rangle \in eval(st, \Sigma')$, for every $i \in \{1, 2, 3, \dots, n\}$, the $\alpha_1.\omega_i$ of Σ (see the translation rule) refers to v'_{ω_i} , i.e. the ω_i -th (from left to right) among v'_1, v'_2, \dots, v'_k .

The reader should now be able to see that the embedded SELECT statement of the translation rule returns the following relation, where $\omega_1, \dots, \omega_n$ are as in the translation rule. (I assume that the TSQL2 string 'dummy' evaluates to the element of D dummy.)³

$$\begin{aligned}
 \text{(A.388)} \quad & eval(st, \text{SELECT DISTINCT 'dummy', } \alpha_1.\omega_2, \alpha_1.\omega_3, \dots, \alpha_1.\omega_n \\
 & \quad \text{VALID } \alpha_1.\omega_1 \\
 & \quad \text{FROM } trans(\phi', \lambda_{init}) \text{ AS } \alpha_1) \\
 & = \{ \langle dummy, v'_{\omega_2}, v'_{\omega_3}, \dots, v'_{\omega_n}; v'_{\omega_1} \rangle \mid \langle v'_1, v'_2, v'_3, \dots, v'_k; v'_t \rangle \in eval(st, \Sigma') \}
 \end{aligned}$$

Let us use $r(st)$ to refer to the relation of (A.388). It should be easy to see from the translation rule and the semantics of (NOSUBPERIOD) (section 5.3.2) that:

$$\begin{aligned}
 \text{(A.389)} \quad & eval(st, \Sigma) = \{ \langle v_t, v_2, v_3, \dots, v_n \rangle \mid \\
 & \quad \langle v_1, v_2, v_3, \dots, v_n; v_t \rangle \in nosubperiod(r(st)) \}
 \end{aligned}$$

Using the definition of *nosubperiod* (section 5.3.2), (A.389) becomes (A.390).

$$\begin{aligned}
 \text{(A.390)} \quad & eval(st, \Sigma) = \{ \langle v_t, v_2, v_3, \dots, v_n \rangle \mid \langle v_1, v_2, v_3, \dots, v_n; v_t \rangle \in r(st), \\
 & \quad \text{and if } \langle v_1, v_2, v_3, \dots, v_n; u_t \rangle \in r(st), \\
 & \quad \text{then } f_D(v_t) \not\sqsubseteq f_D(u_t) \}
 \end{aligned}$$

Replacing $r(st)$ by the relation of (A.388), (A.390) becomes (A.391). (A.391) is equiv-

³ The reader may wonder if v'_{ω_1} is always a valid time-stamp, i.e. if there is any guarantee that $v'_{\omega_1} \in D_T$. Intuitively, this is indeed the case, because v'_{ω_1} corresponds to β_1 , and the syntax of TOP requires β_1 to occur at least once within ϕ' as the first argument of a *Past*, *Perf*, *At*, *Before*, *After*, or *Ntense* operator. The semantics of TOP requires variables that occur at these positions to denote periods, and hence v'_{ω_1} will also denote a period, i.e. $v'_{\omega_1} \in D_P \subseteq D_T$. This, however, will not be proven formally here.

alent to (A.392).

$$\begin{aligned}
 \text{(A.391)} \quad & eval(st, \Sigma) = \{ \langle v_t, v_2, v_3, \dots, v_n \rangle \mid \\
 & v_1 = dummy, v_2 = v'_{\omega_2}, v_3 = v'_{\omega_3}, \dots, v_n = v'_{\omega_n}, v_t = v'_{\omega_1}, \\
 & \langle v'_1, v'_2, v'_3, \dots, v'_k; v'_t \rangle \in eval(st, \Sigma'), \\
 & \text{and if } v_1 = dummy, v_2 = v''_{\omega_2}, v_3 = v''_{\omega_3}, \dots, v_n = v''_{\omega_n}, v_t = v''_{\omega_1}, \\
 & \text{and } \langle v''_1, v''_2, v''_3, \dots, v''_k; v''_t \rangle \in eval(st, \Sigma'), \text{ then } f_D(v_t) \not\sqsubseteq f_D(v_t) \} \\
 \text{(A.392)} \quad & eval(st, \Sigma) = \{ \langle v'_{\omega_1}, v'_{\omega_2}, v'_{\omega_3}, \dots, v'_{\omega_n} \rangle \mid \\
 & \langle v'_1, v'_2, v'_3, \dots, v'_k; v'_t \rangle \in eval(st, \Sigma'), \\
 & \text{and if } \langle v''_1, v''_2, v''_3, \dots, v''_k; v''_t \rangle \in eval(st, \Sigma') \text{ and} \\
 & v'_{\omega_2} = v''_{\omega_2}, v'_{\omega_3} = v''_{\omega_3}, \dots, v'_{\omega_n} = v''_{\omega_n}, \text{ then } f_D(v'_{\omega_1}) \not\sqsubseteq f_D(v'_{\omega_1}) \}
 \end{aligned}$$

(A.392) implies that $eval(st, \Sigma)$ is a snapshot relation of n attributes. Therefore, clause 2 holds.

Proof of clause 3

By the definitions of $\|\phi\|^{M(st), st}$ and $\|\phi\|^{M(st), st, et, lt, g}$ for $\phi \in WHFORMS_2$ (section 3.6), clause 3 becomes:

$$\begin{aligned}
 \text{(A.393)} \quad & \{ \langle f_D(v_1), f_D(v_2), f_D(v_3), \dots, f_D(v_n) \rangle \mid \langle v_1, v_2, v_3, \dots, v_n \rangle \in eval(st, \Sigma) \} \\
 & = \bigcup_{g \in G, et \in PERIODS} \{ \langle g(\beta_1), g(\beta_2), \dots, g(\beta_n) \rangle \mid \|\phi'\|^{M(st), st, et, PTS, g} = T, \\
 & \quad \text{and for no } et' \in PERIODS \text{ and } g' \in G \text{ is it true that} \\
 & \quad \|\phi'\|^{M(st), st, et', PTS, g'} = T, g(\beta_1) \sqsubset g'(\beta_1), \text{ and} \\
 & \quad g(\beta_2) = g'(\beta_2), \dots, g(\beta_n) = g'(\beta_n) \}
 \end{aligned}$$

I prove (A.393) by proving that its left-hand side (LHS) is a subset of its right-hand side (RHS), and that its RHS is a subset of its LHS. I first prove that the LHS is a subset of the RHS. I assume that for some $v_1, \dots, v_n \in D$, $\langle f_D(v_1), \dots, f_D(v_n) \rangle$ is an element of the LHS of (A.393), i.e. that (A.394) holds.

$$\text{(A.394)} \quad \langle v_1, \dots, v_n \rangle \in eval(st, \Sigma)$$

I need to prove that $\langle f_D(v_1), \dots, f_D(v_n) \rangle$ is also an element of the RHS of (A.393), i.e. that for some g and et :

$$\begin{aligned}
 \text{(A.395)} \quad & g \in G \\
 \text{(A.396)} \quad & et \in PERIODS \\
 \text{(A.397)} \quad & f_D(v_1) = g(\beta_1), \dots, f_D(v_n) = g(\beta_n) \\
 \text{(A.398)} \quad & \|\phi'\|^{M(st), st, et, PTS, g} = T \\
 \text{(A.399)} \quad & \text{for no } et' \in PERIODS \text{ and } g' \in G \text{ is it true that} \\
 & \|\phi'\|^{M(st), st, et', PTS, g'} = T, g(\beta_1) \sqsubset g'(\beta_1), \text{ and} \\
 & g(\beta_2) = g'(\beta_2), \dots, g(\beta_n) = g'(\beta_n)
 \end{aligned}$$

(A.394) and (A.392) imply that for some v'_1, \dots, v'_k, v'_t :

$$(A.400) \quad \langle v'_1, \dots, v'_k; v'_t \rangle \in eval(st, \Sigma')$$

$$(A.401) \quad v_1 = v'_{\omega_1}, v_2 = v'_{\omega_2}, \dots, v_n = v'_{\omega_n}$$

$$(A.402) \quad \text{if } \langle v''_1, v''_2, v''_3, \dots, v''_k; v''_t \rangle \in eval(st, \Sigma') \text{ and} \\ v'_{\omega_2} = v''_{\omega_2}, v'_{\omega_3} = v''_{\omega_3}, \dots, v'_{\omega_n} = v''_{\omega_n}, \text{ then } f_D(v'_{\omega_1}) \not\sqsubseteq f_D(v''_{\omega_1})$$

where $\omega_1, \dots, \omega_n$ are as in the translation rule.

(A.400) and clause 3' imply that for some g :

$$(A.403) \quad g \in G$$

$$(A.404) \quad \|\tau_1\|^{M(st),g} = f_D(v'_1), \dots, \|\tau_k\|^{M(st),g} = f_D(v'_k)$$

$$(A.405) \quad \|\phi'\|^{M(st),st,f_D(v'_t),PTS,g} = T$$

(A.395) is the same as (A.403), which is known to be true. I set et as in (A.406). Then, (A.398) follows from (A.405).

$$(A.406) \quad et = f_D(v'_t)$$

(A.400) and clause 2' imply that $v'_t \in D_P$, which in turn implies (A.407). (A.396) follows from (A.406) and (A.407).

$$(A.407) \quad f_D(v'_t) \in PERIODS$$

I now prove (A.397). For every $i \in \{1, 2, 3, \dots, n\}$, since $\beta_i \in VARS$, according to the semantics of TOP:

$$(A.408) \quad g(\beta_i) = \|\beta_i\|^{M(st),g}$$

The definition of $\omega_1, \dots, \omega_n$ in the translation rule implies that :

$$(A.409) \quad \tau_{\omega_i} = \beta_i$$

$$(A.410) \quad \omega_i \in \{1, 2, 3, \dots, k\}$$

(A.409) and (A.408) imply (A.411). (A.410) and (A.404) imply (A.412). (A.411) and (A.412) imply (A.413).

$$(A.411) \quad g(\beta_i) = \|\tau_{\omega_i}\|^{M(st),g}$$

$$(A.412) \quad \|\tau_{\omega_i}\|^{M(st),g} = f_D(v'_{\omega_i})$$

$$(A.413) \quad g(\beta_i) = f_D(v'_{\omega_i})$$

(A.401) and the assumption that $i \in \{1, 2, 3, \dots, n\}$, imply (A.414). (A.414) and (A.413) imply (A.415).

$$(A.414) \quad v'_{\omega_i} = v_i$$

$$(A.415) \quad g(\beta_i) = f_D(v_i)$$

I have proven that for every $i \in \{1, 2, 3, \dots, n\}$, $f_D(v_i) = g(\beta_i)$. Therefore, (A.397) holds.

It remains to prove (A.399). Let us assume that for some $et' \in PERIODS$ and $g' \in G$, (A.416) and (A.417) hold.

$$(A.416) \quad \|\phi'\|^{M(st),st,et',PTS,g'} = T$$

$$(A.417) \quad g(\beta_1) \sqsubset g'(\beta_1), g(\beta_2) = g'(\beta_2), \dots, g(\beta_n) = g'(\beta_n)$$

For $j \in \{1, 2, 3, \dots, k\}$, I set $v_j'' = f_D^{-1}(\|\tau_j\|^{M(st),g'})$, which implies (A.418). I also set $v_t'' = f_D^{-1}(et')$, which implies (A.419).

$$(A.418) \quad \|\tau_1\|^{M(st),g'} = f_D(v_1''), \dots, \|\tau_k\|^{M(st),g'} = f_D(v_k'')$$

$$(A.419) \quad et' = f_D(v_t'')$$

(A.416) and (A.419) imply (A.420). Clause 3', the assumption that $g' \in G$, (A.418), and (A.420) imply (A.421).

$$(A.420) \quad \|\phi'\|^{M(st),st,f_D(v_t''),PTS,g'} = T$$

$$(A.421) \quad \langle v_1'', v_2'', v_3'', \dots, v_k'', v_t'' \rangle \in eval(st, \Sigma')$$

The definition of $\omega_1, \dots, \omega_n$ in the translation rules implies that $\omega_1 \in \{1, 2, 3, \dots, k\}$ and $\tau_{\omega_1} = \beta_1$. Then, from (A.418) we get (A.422). (A.422) and the fact that $\beta_1 \in VARS$ imply (A.423).

$$(A.422) \quad f_D(v_{\omega_1}'') = \|\tau_{\omega_1}\|^{M(st),g'} = \|\beta_1\|^{M(st),g'}$$

$$(A.423) \quad f_D(v_{\omega_1}'') = g'(\beta_1)$$

(A.397) (proven above) and (A.401) imply (A.424). (A.423), (A.424), and (A.417) imply (A.425).

$$(A.424) \quad g(\beta_1) = f_D(v_{\omega_1}')'$$

$$(A.425) \quad f_D(v_{\omega_1}')' \sqsubset f_D(v_{\omega_1}'')$$

For $l \in \{2, 3, \dots, n\}$, the definition of $\omega_1, \dots, \omega_n$ in the translation rule implies that:

$$(A.426) \quad \omega_l \in \{1, 2, 3, \dots, k\}$$

$$(A.427) \quad \tau_{\omega_l} = \beta_l$$

(A.418) and (A.426) imply (A.428). (A.428), (A.427), and the fact that $\beta_l \in VARS$ imply (A.429), which in turn implies (A.430).

$$(A.428) \quad \|\tau_{\omega_l}\|^{M(st),g'} = f_D(v_{\omega_l}'')$$

$$(A.429) \quad \|\beta_l\|^{M(st),g'} = g'(\beta_l) = f_D(v_{\omega_l}'')$$

$$(A.430) \quad v_{\omega_l}'' = f_D^{-1}(g'(\beta_l))$$

Since $l \in \{2, 3, \dots, n\}$, (A.417) implies (A.431). (A.430) and (A.431) imply (A.432).

$$(A.431) \quad g'(\beta_l) = g(\beta_l)$$

$$(A.432) \quad v_{\omega_l}'' = f_D^{-1}(g(\beta_l))$$

(A.397) (proven above) and the fact that $l \in \{2, 3, \dots, n\}$ imply that $g(\beta_l) = f_D(v_l)$, which in turn implies (A.433). (A.432) and (A.433) imply (A.434). (A.434), (A.401), and the fact that $l \in \{2, 3, \dots, n\}$ imply (A.435).

$$(A.433) \quad f_D^{-1}(g(\beta_l)) = v_l$$

$$(A.434) \quad v''_{\omega_l} = v_l$$

$$(A.435) \quad v_l = v'_{\omega_l}$$

(A.434) and (A.435) imply that $v''_{\omega_l} = v'_{\omega_l}$. I have proven that for every $l \in \{2, 3, 4, \dots, n\}$, $v''_{\omega_l} = v'_{\omega_l}$. Hence, (A.436) holds.

$$(A.436) \quad v''_{\omega_2} = v'_{\omega_2}, v''_{\omega_3} = v'_{\omega_3}, \dots, v''_{\omega_n} = v'_{\omega_n}$$

(A.421), (A.436), and (A.425) are against (A.402). Therefore, the hypothesis that there is an $et' \in PERIODS$ and a $g' \in G$, such that (A.416) and (A.417) are satisfied cannot hold. (A.399) has been proven. The proof that the LHS of (A.393) is a subset of the RHS has been completed.

I now prove that the RHS of (A.393) is a subset of the LHS. I assume that for some $g \in G$, $\langle g(\beta_1), g(\beta_2), \dots, g(\beta_n) \rangle$ is an element of the RHS of (A.393), i.e. that for some g and et , (A.437) – (A.440) hold.

$$(A.437) \quad g \in G$$

$$(A.438) \quad et \in PERIODS$$

$$(A.439) \quad \|\phi'\|^{M(st), st, et, PTS, g} = T$$

$$(A.440) \quad \text{for no } et' \in PERIODS \text{ and } g' \in G \text{ is it true that}$$

$$\|\phi'\|^{M(st), st, et', PTS, g'} = T, g(\beta_1) \sqsubset g'(\beta_1), \text{ and}$$

$$g(\beta_2) = g'(\beta_2), \dots, g(\beta_n) = g'(\beta_n)$$

I need to prove that $\langle g(\beta_1), g(\beta_2), \dots, g(\beta_n) \rangle$ is also an element of the LHS of (A.393), i.e. that for some $v_1, \dots, v_n \in D$:

$$(A.441) \quad g(\beta_1) = f_D(v_1), \dots, g(\beta_n) = f_D(v_n)$$

$$(A.442) \quad \langle v_1, \dots, v_n \rangle \in eval(st, \Sigma)$$

I set v_1, \dots, v_n as in (A.443), which implies (A.441).

$$(A.443) \quad v_1 = f_D^{-1}(g(\beta_1)), \dots, v_n = f_D^{-1}(g(\beta_n))$$

It remains to prove (A.442). By (A.392), it is enough to prove that for some $v'_1, v'_2, \dots, v'_k, v'_t$:

$$(A.444) \quad \langle v'_1, \dots, v'_k; v'_t \rangle \in eval(st, \Sigma')$$

$$(A.445) \quad v_1 = v'_{\omega_1}, \dots, v_n = v'_{\omega_n}$$

$$(A.446) \quad \text{if } \langle v''_1, v''_2, v''_3, \dots, v''_k; v''_t \rangle \in eval(st, \Sigma') \text{ and}$$

$$v'_{\omega_2} = v''_{\omega_2}, v'_{\omega_3} = v''_{\omega_3}, \dots, v'_{\omega_n} = v''_{\omega_n}, \text{ then } f_D(v'_{\omega_1}) \not\sqsubset f_D(v''_{\omega_1})$$

where $\omega_1, \dots, \omega_n$ are as in the translation rule.

I set v'_1, \dots, v'_k as in (A.447), which implies (A.448). I also set $v'_t = f_D^{-1}(et)$, which implies (A.449). Clause 3', (A.437), (A.448), (A.449), and (A.439) imply (A.444).

$$(A.447) \quad v'_1 = f_D^{-1}(\|\tau_1\|^{M(st),g}), \dots, v'_k = f_D^{-1}(\|\tau_k\|^{M(st),g})$$

$$(A.448) \quad \|\tau_1\|^{M(st),g} = f_D(v'_1), \dots, \|\tau_k\|^{M(st),g} = f_D(v'_k)$$

$$(A.449) \quad et = f_D(v'_t)$$

I now prove (A.445). (A.443) implies that (A.450) holds for every $i \in \{1, 2, 3, \dots, n\}$. Since $\beta_i \in \text{VAR}_S$, from the semantics of TOP we also get (A.451). (A.450) and (A.451) imply (A.452).

$$(A.450) \quad v_i = f_D^{-1}(g(\beta_i))$$

$$(A.451) \quad g(\beta_i) = \|\beta_i\|^{M(st),g}$$

$$(A.452) \quad v_i = f_D^{-1}(\|\beta_i\|^{M(st),g})$$

The definition of $\omega_1, \dots, \omega_n$ in the translation rule implies that:

$$(A.453) \quad \beta_i = \tau_{\omega_i}$$

$$(A.454) \quad \omega_i \in \{1, 2, 3, \dots, k\}$$

Using (A.453), (A.452) becomes (A.455). (A.454) and (A.447) imply (A.456).

$$(A.455) \quad v_i = f_D^{-1}(\|\tau_{\omega_i}\|^{M(st),g})$$

$$(A.456) \quad v'_{\omega_i} = f_D^{-1}(\|\tau_{\omega_i}\|^{M(st),g})$$

(A.455) and (A.456) imply that $v_i = v'_{\omega_i}$. I have proven that for every $i \in \{1, 2, 3, \dots, n\}$, $v_i = v'_{\omega_i}$. Hence, (A.445) holds.

It remains to prove (A.446). Let us assume that:

$$(A.457) \quad \langle v''_1, v''_2, v''_3, \dots, v''_k, v''_t \rangle \in \text{eval}(st, \Sigma')$$

$$(A.458) \quad v'_{\omega_2} = v''_{\omega_2}, v'_{\omega_3} = v''_{\omega_3}, \dots, v'_{\omega_n} = v''_{\omega_n}$$

We need to prove that $f_D(v'_{\omega_1}) \not\sqsubset f_D(v''_{\omega_1})$. Let us assume that this is not true, i.e. that (A.459) holds.

$$(A.459) \quad f_D(v'_{\omega_1}) \sqsubset f_D(v''_{\omega_1})$$

Clause 3' and (A.457) imply that for some g' :

$$(A.460) \quad g' \in G$$

$$(A.461) \quad \|\tau_1\|^{M(st),g'} = f_D(v''_1), \dots, \|\tau_k\|^{M(st),g'} = f_D(v''_k)$$

$$(A.462) \quad \|\phi'\|^{M(st),st,f_D(v'_t),PTS,g'} = T$$

I set et' as in (A.463). Then (A.462) implies (A.464).

$$(A.463) \quad et' = f_D(v''_t)$$

$$(A.464) \quad \|\phi'\|^{M(st),st,et',PTS,g'} = T$$

(A.457) and clause 2' imply that $v_t'' \in D_P$, which in turn implies that $f_D(v_t'') \in PERIODS$. Then, (A.463) implies that:

$$(A.465) \quad et' \in PERIODS$$

For $i \in \{1, 2, 3, \dots, n\}$, (A.461) and (A.454) imply (A.466). (A.466), (A.453), and the fact that $\beta_i \in VARS$ imply (A.467).

$$(A.466) \quad \|\tau_{\omega_i}\|^{M(st),g'} = f_D(v_{\omega_i}'')$$

$$(A.467) \quad \|\beta_i\|^{M(st),g'} = g'(\beta_i) = f_D(v_{\omega_i}'')$$

(A.441) (which holds because of (A.443)) and the fact that $i \in \{1, 2, 3, \dots, n\}$ imply (A.468). (A.445) (proven above) and the fact that $i \in \{1, 2, 3, \dots, n\}$ imply (A.469). (A.468) and (A.469) imply (A.470).

$$(A.468) \quad g(\beta_i) = f_D(v_i)$$

$$(A.469) \quad v_i = v_{\omega_i}'$$

$$(A.470) \quad g(\beta_i) = f_D(v_{\omega_i}')$$

(A.470) and (A.467) were proven for $i \in \{1, 2, 3, \dots, n\}$. For $i = 1$, from (A.470) we get (A.471), and from (A.467) we get (A.472). (A.459), (A.471), and (A.472) imply (A.473).

$$(A.471) \quad g(\beta_1) = f_D(v_{\omega_1}')$$

$$(A.472) \quad g'(\beta_1) = f_D(v_{\omega_1}'')$$

$$(A.473) \quad g(\beta_1) \sqsubset g'(\beta_1)$$

For $l \in \{2, 3, \dots, n\}$, from (A.470) we get (A.474), and from (A.467) we get (A.475). (A.458) and the fact that $l \in \{2, 3, \dots, n\}$ imply (A.475). (A.474) and (A.475) imply (A.476).

$$(A.474) \quad g(\beta_l) = f_D(v_{\omega_l}')$$

$$(A.475) \quad g'(\beta_l) = f_D(v_{\omega_l}'')v_{\omega_l}' = v_{\omega_l}''$$

$$(A.476) \quad g(\beta_l) = f_D(v_{\omega_l}'')$$

(A.476) and (A.475) imply that $g(\beta_l) = g'(\beta_l)$. I have proven that for every $l \in \{2, 3, \dots, n\}$, $g(\beta_l) = g'(\beta_l)$. Therefore, (A.477) holds.

$$(A.477) \quad g(\beta_2) = g'(\beta_2), g(\beta_3) = g'(\beta_3), \dots, g(\beta_n) = g'(\beta_n)$$

(A.465), (A.460), (A.464), (A.473), and (A.477) are against (A.440). Therefore, the hypothesis that (A.459) is true cannot hold, i.e. $f_D(v_{\omega_1}') \not\sqsubset f_D(v_{\omega_1}'')$. (A.446) has been proven. The proof that the RHS of (A.393) is a subset of the LHS has been completed.